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Diffractive A_1 production by neutrinos

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A phenomenological study of diffractive $\pi\rho$ production by neutrinos in the A_1 region is performed. The difference between resonant and nonresonant (Deck-type) production is worked out. Interference effects are included. Numerical results for the mass and decay angular distributions are given.

I. INTRODUCTION

For many years much experimental effort has been put into establishing the A_1 meson as a genuine resonance as is demanded by our current theoretical belief. No convincing evidence has been found in purely hadronic reactions[1,2] as, for instance, in $\pi N \to (\pi\rho)N$. Although experiments have by now acquired sufficient statistics to allow one to do partial-wave analyses, no strong phase variation of the 1^+ partial wave has been observed which would be an unambigous signal for a resonance. Only recently the discovery of the heavy lepton τ and its decay into $\nu_t(\pi\rho)$ showing a strong enhancement in the $(\pi\rho)$ mass distribution near the expected A_1 mass gives strong support for the existence of the A_1 as a resonance.[3] The question of the existence of the A_1 became even more interesting since other axial-vector mesons, namely K_A (the 1^+ state in the so-called Q region) and ψ_A (the $^3P_1$ state at 3.51 GeV), seem to be experimentally confirmed.[1,4]

The difficulties in the diffractive hadronic reactions have been due to the fact that the data can be largely reproduced by nonresonant Deck-type models.[5] Even if the A_1 is a resonance, its contribution to the $\pi\rho$ system in the final state cannot be separated from the nonresonant Deck contribution in a clear way.

A clearer situation is presumably present in the diffractive production of the A_1 system by neutrinos[6,7]:

$$\nu + N \to \mu + N + (\pi\rho)\,. \tag{1}$$

If the A_1 really exists and moreover dominates the hadronic weak axial-vector current, then in reaction (1) the lepton pair couples weakly to the A_1 which in turn is elastically scattered off the nucleon [see Fig. 1(b)]. The mechanism is similar to photoproduction or electroproduction of ρ^0 mesons where the photon couples to the vector mesons dominating the electromagnetic current. Also in this case one has a resonant amplitude as well as a Deck-type background (Söding model[8]). From the experimental data[9] on ρ^0 photoproduction it has been found that the resonant contribution is the dominant one. We can therefore expect that also in the reaction (1) resonant A_1 production should be the main contribution. The essential point is that reaction (1) proceeds via elastic scattering of the A_1, whereas in the reaction $\pi N \to (\rho\pi)N$, the A_1 would have to be produced by diffractive excitation which is an order of magnitude smaller than elastic scattering.

Various authors have estimated the total A_1-resonance production rate by neutrinos.[6,7] For instance, in Ref. 7 the diffractive $A_1^{\pm}$ production rate for an incoming neutrino energy of $E \sim 50$ GeV has been predicted to be $5\text{–}20 \times 10^{-40}$ cm^2. Where-

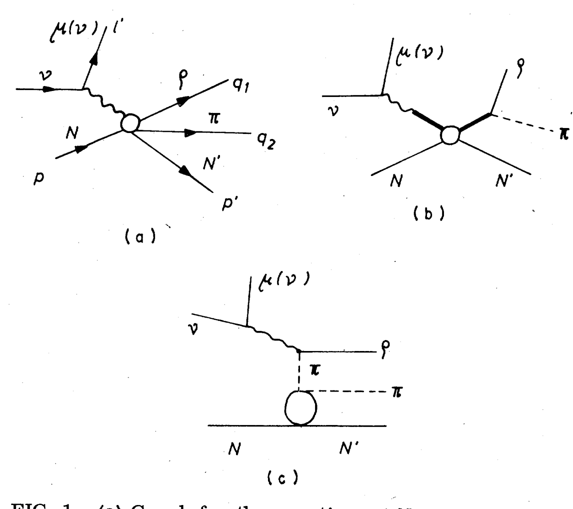

FIG. 1. (a) Graph for the reaction $\nu + N \to \mu(\nu) + N + \rho + \pi$. (b) Graph for resonance production. (c) Deck mechanism for $\rho\pi$ production.

as diffractive ρ^+ production has already been observed experimentally, for A_1^+ production only upper bounds of 11×10^{-40} cm^2 or 9×10^{-40} cm^2 have been obtained[10] in experiments with the Fermilab 15-ft bubble chamber or with BEBC at CERN, respectively. On the basis of these results, however, one cannot decide whether the A_1 is a resonance and how the $\pi\rho$ system is produced. Further experimental information can be expected in the future.

In our previous analysis[7] of neutrino production of vector and axial-vector mesons, we have worked out the kinematic details necessary for an experimental investigation and were mainly interested in general dynamical questions. In the present paper we shall study $\pi\rho$ production in the A_1 region in detail. We compare pure resonance production with the nonresonant Deck model paying particular attention to the differences in the mass distributions and decay angular distributions in the cross sections σ_U, σ_L, etc. In analogy to the Söding model for $\pi^+\pi^-$ photoproduction we also consider the interference of the resonant amplitude with the Deck background. This is most likely a reasonably good representation of the actual situation.

An essential feature of the underlying picture is the A_1 dominance of the hadronic weak axial-vector current which is expected to be valid in the small-Q^2 region. Because of the uncertainty in the Q^2 behavior at large Q^2 we restrict ourselves in the actual calculations to a fixed low value of Q^2, i.e., $Q^2=0.4$ GeV^2. Of course the numerical results also depend on the precise values of the $\pi\rho A_1$ coupling constants. Needless to say, the neutral-current reaction

$$\nu+N\rightarrow\nu+N+A_1^0 \tag{2}$$

can be used to determine the coupling of the axial-vector part of the weak neutral hadronic current.

Section II gives a short compendium of the most important kinematical formulas for a three-hadron final state in neutrino production. In Sec. III we study pure resonance production. The Deck mechanism is treated in Sec. IV. In Sec. V we consider the interference between the resonant amplitude and the Deck amplitude. Finally Sec. VI contains a discussion of the numerical results.

II. KINEMATICS

In order to describe reactions (1) or (2) we use the standard variables ν, Q^2, s, t, and ϕ as defined in Ref. 7. The four-momenta of the external particles are as denoted in Fig. 1(a). Since we are treating here a three-hadron final state, we need three further variables: $M_A{}^2=q'^2$, where $q'=q_1+q_2$, and the polar and azimuthal angles θ^*, ϕ^* of $\vec{q}_1$ in the $\pi\rho$ rest system $\vec{q}\,'=0$. The cross section can then be written in the following form[7]:

$$\frac{d\sigma}{dE'd\Omega_l dt d\phi d\cos\theta^* d\phi^* dM_A{}^2} = \Gamma\frac{d\sigma^W}{dtd\phi d\cos\theta^* d\phi^* dM_A{}^2}, \tag{3}$$

where E' and Ω_l are the energy and the solid angle of the outgoing lepton in the laboratory system. Γ is the flux factor of the intermediate vector boson:

$$\Gamma=\frac{G^2}{4\pi^3}\frac{E'}{E}\frac{Q^2}{(1-\epsilon)}\frac{(s-M^2)}{2M}.$$

E is the incoming neutrino energy, and ϵ is given by

$$\epsilon=\left(1+\frac{2(Q^2+\nu^2)}{4E(E-\nu)-Q^2}\right)^{-1}.$$

The virtual- (intermediate-) boson cross section is decomposed as

$$\frac{d\sigma^W}{dtd\phi d\cos\theta^* d\phi^* dM_A{}^2}=\frac{1}{2\pi}\{\sigma_U+\epsilon\sigma_L+\epsilon\cos2\phi\sigma_T+\epsilon\sin2\phi\sigma_T'+[2\epsilon(1+\epsilon)]^{1/2}(\cos\phi)\sigma_I+[2\epsilon(1+\epsilon)]^{1/2}\sin\phi\sigma_I'$$
$$+\eta((1-\epsilon^2)^{1/2}\sigma_C+[2\epsilon(1-\epsilon)]^{1/2}(\cos\phi)\sigma_{CL}+[2\epsilon(1-\epsilon)]^{1/2}(\sin\phi)\sigma_{CL}')\}, \tag{4}$$

where σ_U is a shorthand notation for $d\sigma_U/dtd\cos\theta^*\,d\phi^* dM_A{}^2$, etc. The various cross-section parts correspond to definite-helicity states of the intermediate boson.[7]

It is useful to introduce helicity amplitudes

$$a_\lambda=\langle\pi,\rho,N|A^\mu(0)|N\rangle\epsilon_\mu(\lambda)(-1)^\lambda, \tag{5}$$

where λ denotes the helicity of the incoming vector boson, the helicity states of the nucleons and of the outgoing ρ meson not being indicated. A^μ is the weak hadronic axial-vector current. As we are interested only in a purely diffractive process we shall not include the corresponding vector-current matrix element.

In terms of the helicity amplitudes (5) the cross sections are given by

$$
\begin{aligned}
\sigma_U &= \mathfrak{N}\tfrac{1}{2}(|a_+|^2 + |a_-|^2)\,,\\
\sigma_L &= \mathfrak{N}\,|a_0|^2\,,\\
\sigma_T &= -\mathfrak{N}\,\mathrm{Re}(a_+a_-^*)\,,\\
\sigma_I &= \mathfrak{N}\frac{1}{\sqrt{2}}\,\mathrm{Re}[(a_+ - a_-)a_0^*]\,,\\
\sigma'_{CL} &= -\mathfrak{N}\frac{1}{\sqrt{2}}\,\mathrm{Im}[(a_+ - a_-)a_0^*]\,,\\
\sigma'_T &= -\mathfrak{N}\,\mathrm{Im}(a_+a_-^*)\,,\\
\sigma'_I &= \mathfrak{N}\frac{1}{\sqrt{2}}\,\mathrm{Im}[(a_+ + a_-)a_0^*]\,,\\
\sigma_C &= \mathfrak{N}(-\tfrac{1}{2})[|a_+|^2 - |a_-|^2]\,,\\
\sigma_{CL} &= \mathfrak{N}\left(-\frac{1}{\sqrt{2}}\right)\mathrm{Re}[(a_+ + a_-)a_0^*]
\end{aligned}
\tag{6}
$$

with

$$\mathfrak{N} = \frac{\tilde{q}}{(2\pi)^4 128 q^* \sqrt{s}\,(s - M^2) M_A}\,,$$

where $\tilde{q}$ is the momentum of the ρ meson in the A_1 rest system and q^* is the virtual-boson momentum in the hadronic c.m. system.

III. RESONANCE CONTRIBUTION

In this section we assume that the A_1 exists. If moreover it dominates the hadronic axial-vector current, the simplest way to produce it diffractively in neutrino scattering is by elastic scattering of A_1 on the nucleon as illustrated in Fig. 1(b). The helicity amplitude for A_1 production by an intermediate vector boson $W^\pm$ is denoted by $A_\lambda^{\lambda'}$ where λ and λ' are the helicities of the $W^\pm$ and A_1, respectively. In order to specify $A_\lambda^{\lambda'}$ assumptions about the reaction mechanisms are necessary. In ρ^0 photoproduction and electroproduction it has been shown[9,11] that s-channel helicity conservation is fulfilled to a good approximation. It is reasonable to assume it to be valid also in A_1 neutrino production. This means that only the following helicity amplitudes do not vanish:

$$
\begin{aligned}
A_1^1 = A_{-1}^{-1} &= i s\, \sigma_{A_1N}^{\mathrm{tot}} e^{At/2} C_A \frac{m_A^2}{m_A^2 + Q^2}\,,\\
A_0^0 &= \xi_A \frac{\sqrt{Q^2}}{m_A} A_1^1\,,
\end{aligned}
\tag{7}
$$

with $m_A = 1.1$ GeV. C_A measures the coupling strength of the A_1 to the axial current [see Eqs. (57) and (58) in Ref. 7]. The values of 26 mb for $\sigma_{A_1N}^{\mathrm{tot}}$ and 8 GeV^{-2} for A are taken as suggested by the quark model. Furthermore, $\xi_A^2 = 0.4$ is used which corresponds to the value as measured in ρ^0 electroproduction. The Q^2 behavior in Eq. (7) follows that of a simple A_1 pole which means that we restrict ourselves to $Q^2 < 1$ GeV^2. The helicity amplitude taking into account the decay $A_1 \to \rho\pi$ is then given by

$$a_\lambda = A_\lambda^\lambda \frac{1}{[q'^2 - m_A^2 + i m_A \Gamma(q'^2)]}\,\epsilon'_\alpha(\lambda, q')\left(m_A g_s g^{\alpha\beta} + \frac{g_d}{4m_A} q_2^\beta q_1^\alpha\right)\epsilon_\beta^*(q_1)\,, \tag{8}$$

where ϵ'_α is the polarization vector of the decaying A_1 and ϵ_β is that of the ρ. The couplings g_s and g_d are the $A_1\pi\rho$ coupling constants. From Eq. (8) the cross sections follow as:

$$
\begin{aligned}
\sigma_U = \mathfrak{N}\tfrac{1}{2}|A_1^1|^2 &\frac{1}{(q'^2 - m_A^2)^2 + m_A^2\Gamma^2}\\
&\times\left[m_A^2 g_s^2\left(2 + \frac{1}{m_\rho^2}\tilde{q}^2\sin^2\theta_S\right) + \left(\frac{g_d}{4m_A}\right)^2 \tilde{q}^2 \sin^2\theta_S\left(-m_\pi^2 + \frac{(q_1\cdot q_2)^2}{m_\rho^2}\right) + \frac{g_s g_d}{2}\tilde{q}^2\sin^2\theta_S\left(1 + \frac{(q_1\cdot q_2)}{m_\rho^2}\right)\right],
\end{aligned}
\tag{9}
$$

$$
\begin{aligned}
\sigma_L = \mathfrak{N}|A_0^0|^2 &\frac{1}{(q'^2 - m_A^2)^2 + m_A^2\Gamma^2}\\
&\times\left[m_A^2 g_s^2\left(1 + \frac{1}{m_\rho^2}\tilde{q}^2\cos^2\theta_s\right) + \left(\frac{g_d}{4m_A}\right)^2 \tilde{q}^2\cos^2\theta_s\left(-m_\pi^2 + \frac{(q_1\cdot q_2)^2}{m_\rho^2}\right) + \frac{g_s g_d}{2}\tilde{q}^2\cos^2\theta_s\left(1 + \frac{(q_1\cdot q_2)}{m_\rho^2}\right)\right].
\end{aligned}
\tag{10}
$$

θ_s is the polar angle of the ρ in the s-channel helicity system with the z axis in the direction of $-\vec{p}'$. $\Gamma(q'^2)$ is the mass-dependent A_1 width:

$$\Gamma = \frac{\tilde{q}}{12\pi}\frac{1}{M_A^2 m_\rho^2}\left[g_s^2 m_A^2(\tilde{q}^2 + 3m_\rho^2) + \frac{g_d^2\tilde{q}^4}{16} + \frac{g_s g_d}{2} m_A \tilde{q}^2(\tilde{q}^2 + m_\rho^2)^{1/2}\right]. \tag{11}$$

Note that σ_U and σ_L exhibit no dependence on the azimuthal decay angle as a consequence of s-channel helicity conservation.

The heavy-lepton decay $\tau \to A_1\nu_\tau$ indicates[3] an A_1 width of 200–250 MeV and a mass of 1.1 GeV. In principle the coupling C_A is determined by the branching ratio $\Gamma(\tau\to A_1\nu_\tau)/\Gamma(\tau\to e\nu\nu_\tau)$.[12] Assuming that the decay $\tau\to(3\pi)\nu_\tau$ is due to $\tau\to A_1\nu_\tau$ the data[3] only give a value of C_A between 0.06 and 0.18 because of the large experimental uncertainties. Hence in order to get definite numbers for the couplings g_s, g_d, and C_A we have to rely on models. Assuming throughout $\Gamma=250$ MeV and $m_A=1.1$ GeV we shall discuss here two cases for charged-A_1 production:

(i) Pure S wave for the $A_1\to\rho\pi$ decay leading to $g_s=3.4$ and $g_d=-9.3$. The A_1-current coupling is given by assuming the validity of the Weinberg sum rules in the one-pole saturation[13] as $C_A=0.12$. [Note that this value of C_A corresponds to Eq. (58) of Ref. 7, whereas the value following from Eq. (57) seems to be already excluded by the experimental data.[10]]

(ii) Hard-pion technique as used in Ref. 14 relates the $A_1\rho\pi$ to the $\rho\pi\pi$ coupling. With $\Gamma_\rho=152$ MeV and $\gamma_\rho^2/4\pi=2.6$ but without relying on the simplest form of the Weinberg sum rules in the one-pole approximation (see Appendix A for details), one gets $g_s=3.5$, $g_d=6.2$, and $C_A=0.16$.

IV. DECK MODEL

In this section we shall study the Deck mechanism for process (1). This is important for two reasons: Firstly, it would be the dominant mechanism for this process if the A_1 were not a resonance. Secondly, even if A_1 is a resonance, the Deck graph [Fig. 1(c)] may represent an appreciable background to A_1 production.

The Deck model has been extensively studied[5] in the phenomenological treatment of the process $\pi N\to(\rho\pi)N$. We apply the same mechanism to our case [Fig. 1(c)]. Here the axial-vector current couples to the $\pi\rho$ system and the pion is subsequently scattered diffractively off the nucleon. We neglect the analogous graph where a ρ is exchanged instead of a π. For the reaction $\pi N\to(\rho\pi)N$ it has been explicitly shown in Ref. 15 that its contribution is much smaller. An analogous estimate for our case which is straightforward but more lengthy gives a similar result. Then the corresponding matrix element for Eq. (5) is

$$\begin{aligned}\langle \rho(q_1),\pi(q_2),N|A^\mu(0)|N\rangle\\ &=\frac{A_{\pi N}(s_1,t)}{(t_1-m_\pi^{\,2})}\\ &\quad\times[G_1(Q^2,t_1)g^{\mu\nu}+G_2(Q^2,t_1)(q-q_1)^\nu q_1^\mu]e_\nu^*(q_1)\,,\end{aligned}\tag{12}$$

where $s_1=(q_2+p')^2$, $t_1=(q-q_1)^2$. $A_{\pi N}$ is the elastic πN-scattering amplitude which we write as

$$A_{\pi N}(s_1,t)=i\sigma_{\rm tot}^{\pi N}s_1e^{At/2}\,,\tag{13}$$

where $\sigma_{\rm tot}^{\pi N}$ is the total πN cross section (taken to be 24 mb) and $A\simeq 8$ (GeV/c)$^{-2}$ is the slope of the differential cross section.

As in previous applications of the Deck model to strong-interaction processes the Reggeized form of π exchange gives a better description of the data, we shall use it here, too. This means that the pion propagator in Eq. (12) is replaced by

$$\frac{1}{t_1-m_\pi^{\,2}}\to\frac{\alpha'[\frac{1}{2}(M_A^{\,2}-u_1)]^{\alpha_\pi(t_1)}}{\alpha_\pi(t_1)}e^{-i\pi\alpha_\pi(t_1)/2}\,,\tag{14}$$

where $u_1=(q-q_2)^2$ and $\alpha_\pi(t_1)=\alpha'(t_1-m_\pi^2)$, $\alpha'=0.9$ GeV^2. G_1 and G_2 of Eq. (12) are the couplings of the $\pi\rho$ system to the axial-vector current. We can write

$$\begin{aligned}G_1(Q^2,t_1)&=C_Am_A\,g_s(Q^2,t_1)\frac{m_A^{\,2}}{(Q^2+m_A^{\,2})}\,,\\ G_2(Q^2,t_1)&=C_A\,\frac{1}{4m_A}\,g_d(Q^2,t_1)\,\frac{m_A^{\,2}}{(Q^2+m_A^{\,2})}\,.\end{aligned}\tag{15}$$

Here we have assumed the Q^2 behavior to be essentially given by a polelike behavior with an effective mass of the $\pi\rho$ system of $m_A=1.1$ GeV. The remaining Q^2 and t_1 dependence of g_s and g_d is expected to be smooth. In order to be able to compare with the resonant case we shall determine the couplings g_s, g_d, and C_A in a way analogous to Sec. III. The underlying idea is that those results of current algebra we are concerned with here may remain valid even if the A_1 does not exist as a resonance (see Ref. 13).

For the two cases considered we then have

(i) g_s, g_d, and C_A as given for case (i) in Sec. III.

(ii) g_s and g_d as in Eq. (A3) with $q_A^{\,2}=-Q^2$ and $k^2=t_1$, and $C_A=0.16$.

The resulting formulas for the cross sections can be worked out in a straightforward way. The expressions for σ_U and σ_L are given in Appendix B.

V. INTERFERENCE OF RESONANT AND DECK AMPLITUDE

If the A_1 is a resonance then, as already mentioned, we have to take into account the interference between the resonant amplitude and the Deck amplitude. We proceed in a way analogous to the Söding model[8] for $\pi^+\pi^-$ photoproduction by taking the sum of the graphs Fig. 1(b) and Fig. 1(c). For calculating the coupling of the axial current to the $\pi\rho$ system we again invoke our basic assumption of A_1 dominance [in Fig. 1(c) as well as in Fig. 1(b)]. This means that the sum rules are evaluated in the π, ρ, and A_1 pole approximation. The results are the same as in the preceding sections. The total helicity amplitude is then the sum of the amplitudes of Eq. (8) and that following from Eqs. (12) and (5) with the numerical values of the couplings corresponding to the two cases considered in Secs. III and IV.

We are aware of the fact that this might lead to some double counting because of resonance formation due to $\pi\rho$ rescattering in the Deck mechanism. Since the $\pi\rho$ partial-wave amplitudes are unknown, a clean treatment of this problem is practically impossible at the present stage of investigation. From a similar analysis of photoproduction[16] one can expect that our results will not be influenced numerically very much.

The cross sections are then obtained from Eq. (6). The formulas for σ_U and σ_L are again given in Appendix B.

VI. NUMERICAL RESULTS AND DISCUSSION

Important information on the production mechanism of the $\pi\rho$ system is to be expected from the $\pi\rho$ mass distribution. We have calculated $d\sigma_U/dM_A{}^2$ and $d\sigma_L/dM_A{}^2$ integrating over t and the decay angles θ^* and ϕ^*, taking as a typical example $s=50$ GeV^2 and $Q^2=0.4$ GeV^2 ($\nu=26.4$ GeV). For experimental reasons it will certainly be necessary to sum over some Q^2 range. The chosen value $Q^2=0.4$ GeV^2 would then roughly correspond to an average value of $0.1 \leq Q^2 \leq 1$ GeV^2, where our model assumptions should be fulfilled.

The results for the cases (i) and (ii) are shown in Figs. 2 and 3, respectively. It turns out that in σ_U and $\sigma_U+\epsilon\sigma_L$ the resonant contribution is larger than the Deck background. This is particularly true for case (i) where the Deck contribution is very much suppressed. Note, however, that in our case (ii) in $d\sigma_L/dM_A{}^2$ the Deck and resonant parts are of comparable magnitude. In both cases the mass distribution due to the Deck graph alone is much flatter than that of the resonant graph. This is in contrast to the hadronic case $\pi N \rightarrow (\rho\pi)N$, where the Deck contribution peaks already near $M_A \simeq 1.1$ GeV. The reason lies in the different nature of the coupling involved and in the different kinematical situation (Q^2 spacelike). If the couplings are like in case (ii), the Deck background by interfering with the resonant part contributes sizably to the cross section. Quite generally the cross section following from case (ii) is larger than that of case (i) by approximately a factor of 2. This is mainly due to the different values of C_A. The influence of the Deck

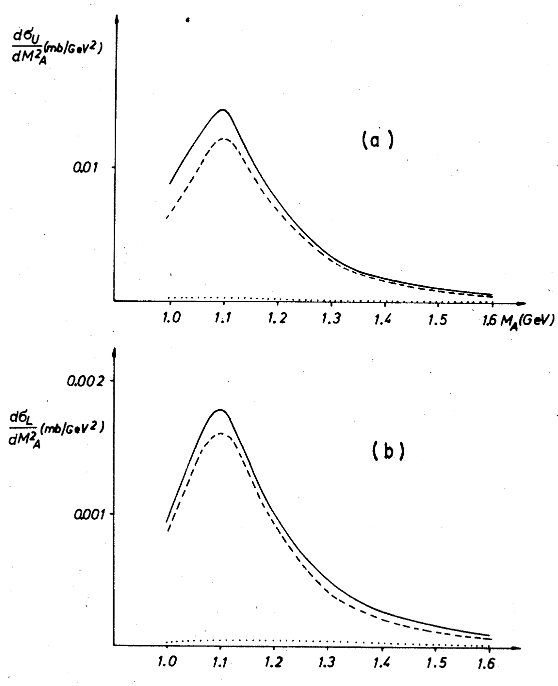

FIG. 2. (a) and (b): The cross sections $d\sigma_U/dM_A{}^2$ and $d\sigma_L/dM_A{}^2$ for the case (i) (pure S wave) for $Q^2=0.4$ GeV^2 and $s=50$ GeV^2. Dashed line: resonant contribution. Dotted line: Deck contribution. Solid line: total contribution.

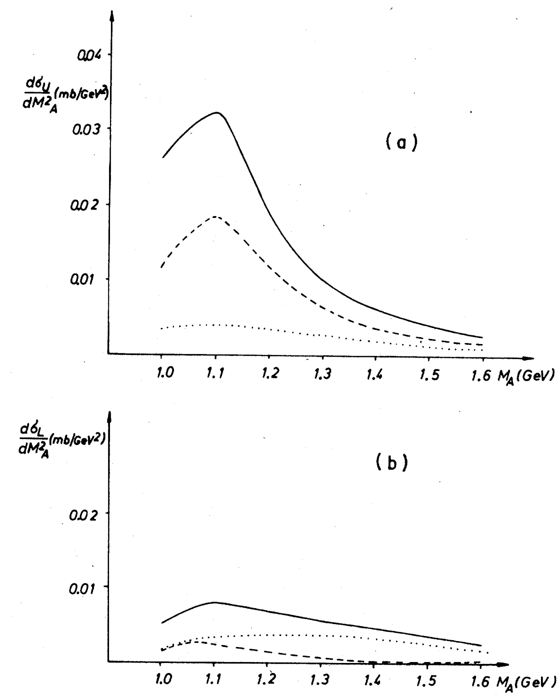

FIG. 3. (a) and (b): The cross sections $d\sigma_U/dM_A{}^2$ and $d\sigma_L/dM_A{}^2$ for the case (ii) (hard-pion technique) for $Q^2=0.4$ GeV and $s=50$ GeV^2. Dashed line: resonant contribution. Dotted line: Deck contribution. Solid line: total contribution.

background can be seen even more clearly in the θ^* distribution. This is shown in Figs. 4(a) and 4(b), where we have plotted $d(\sigma_U + \epsilon\sigma_L)/d\cos\theta^*$ ($\epsilon = 0.8$), again for the two cases integrating over t, ϕ^*, and M_A^2 from 1.0 GeV^2 to 2.56 GeV^2. Whereas the pure resonance part is symmetric in $\cos\theta^*$ and rather flat, the Deck and the total contributions show a pronounced asymmetry.

We also have looked at the other cross-section parts of Eq. (4) σ_T, σ_I, etc., but shall not explicitly present them here because they turn out to be much smaller than σ_U and σ_L. They vanish for the pure resonance case and s-channel helicity conservation. Hence one expects only a rather weak dependence on ϕ of the cross section in Eq. (4).

Of course our numerical results depend on various assumptions as the $A_1\rho\pi$ coupling constants, the A_1-nucleon cross section, etc. The basic hypothesis, however, concerns the way the A_1 couples to the axial-vector current. If A_1 dominance holds we would expect that a decision between resonant or nonresonant $\pi\rho$ production should be more clearly possible in neutrino scattering than in pure hadronic reactions because the resonance mechanism is more pronounced. On the other hand, in case that the A_1 does not exist as a resonance, the Deck contribution is the only one. It may, however, happen that the A_1 is a resonance but by some mechanism does not couple to the axial current with the strength as expected. Then the resonance contribution will also be suppressed with respect to the Deck background.

It is obvious that our considerations apply also to the neutral-current reaction (2). One has just to take the appropriate value for C_A, the coupling of the A_1^0 to the neutral axial-vector current. In the Weinberg-Salam model, for instance, the A_1^0 production cross section should be one half of the A_1^+ cross section.

If the ideas outlined above are right, they should be valid also for neutrino production of K_A (decaying into πK^*) and D_A (decaying into $D^*\pi$), where K_A and D_A denote the axial partners of K^* and D^*, respectively.

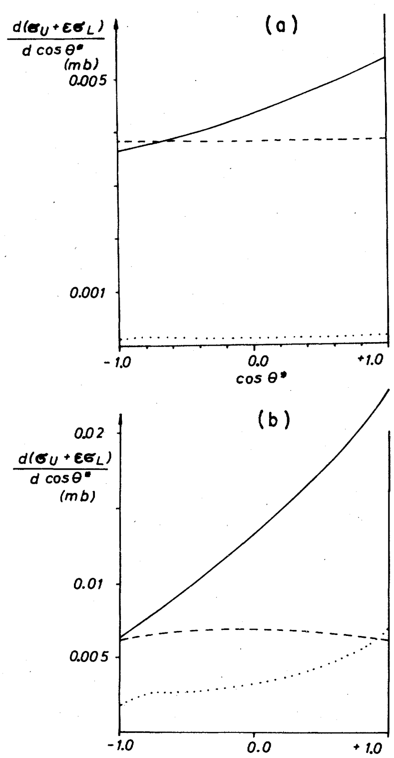

FIG. 4. (a) and (b): $d(\sigma_U + \epsilon\sigma_L)/d\cos\theta^*$ for cases (i) and (ii), respectively, for $Q^2 = 0.4\ \text{GeV}^2$, $s = 50\ \text{GeV}^2$, $\epsilon = 0.8$. Dashed line: resonant contribution. Dotted line: Deck contribution. Solid line: total contribution.

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APPENDIX A

Following Ref. 14 one gets for the off-shell $A_1\rho\pi$ couplings

$$g_s = \frac{\gamma_\rho}{\sqrt{\alpha}}\left[1 - \frac{q_A^2}{m_A^2}\left(1 - \frac{\delta}{2}\,\alpha\right) - \frac{q_1^2}{m_A^2}\,\alpha\left(1 + \frac{\delta}{2} - \frac{m_A^2}{m_\rho^2}\right) - \frac{k^2}{m_A^2}\,\alpha\,\frac{\delta}{2}\right],$$

$$g_d = -4\gamma_\rho\sqrt{\alpha}\,\delta\,, \tag{A1}$$

with $\alpha = m_A^2/F_\pi^2\gamma_A^2$, $\gamma_\rho^2/4\pi \simeq 2.6$, and q_A, q_1, and k the four momenta of the A_1, ρ, and π, respectively. α and δ are unknown parameters. The ρ width is then given by

$$\Gamma(\rho \to \pi\pi) = \frac{\gamma_\rho^2}{16\pi}\,\frac{m_\rho}{12}\left(1 - \frac{4m_\pi^2}{m_\rho^2}\right)^{3/2}\left(1 + \alpha\,\frac{(1-\delta)}{2}\right)^2. \tag{A2}$$

The simplest form of the Weinberg sum rule in the pole approximation would give $\alpha = 1$ and consequently $\gamma_A = 2\gamma_\rho$. Eq. (A2) with $\Gamma(\rho \to \pi\pi) = 152$

MeV would then demand $\delta \simeq -1$. This, however, would lead to an A_1 width of ~70 MeV. In case (ii) we prefer not to use this simple form of the Weinberg sum rules, but rather to fix α and δ by the widths of the ρ and A_1. With $\Gamma(A_1 \to \rho\pi) = 250$ MeV this leads to $\alpha = 1.9$ and $\delta = -0.2$ which means $\gamma_A = 1.49\ \gamma_\rho$. Note that g_d is a constant, whereas g_s shows a dependence on the off-shell masses. Putting ρ on shell one gets

$$g_s = 8.4\left(1 - 0.58\,\frac{q_A^{\,2}}{m_A^{\,2}} + 0.09\,\frac{k^2}{m_A^{\,2}}\right), \qquad g_d = 6.2\,. \tag{A3}$$

APPENDIX B

The contribution of the Deck graph Fig. 1(c) to σ_U and σ_L is given by

$$\sigma_U = \mathfrak{N}|\mathfrak{D}|^2\{h_1 + h_2 \tfrac{1}{2}[(q_1^x)^2 + (q_1^y)^2]\},$$

$$\sigma_L = \mathfrak{N}|\mathfrak{D}|^2\{-h_1 + h_2(1/Q^2)(q^* q_1^0 - q^0 q_1^z)^2\},$$

with

$$\mathfrak{D} = A_{\pi N}\,\frac{\alpha'[\tfrac{1}{2}(M_A^{\,2} - u_1)]^{\alpha_\pi(t_1)}}{\alpha_\pi(t_1)}\,e^{-i\pi\alpha_\pi(t_1)/2},$$

$$\mathfrak{N} = \tilde{q}[(2\pi)^4 128 q^* \sqrt{s}\,(s - M^2) M_A]^{-1},$$

$$h_1 = |G_1|^2,$$

$$h_2 = \frac{|G_1|^2}{m_\rho^{\,2}} + |G_2|^2\left[-t_1 + \frac{(Q^2 + t_1 + m_\rho^{\,2})^2}{4m_\rho^{\,2}}\right] + 2G_1G_2\left[1 - \frac{(Q^2 + t_1 + m_\rho^{\,2})}{2m_\rho^{\,2}}\right],$$

where the components of q_1 are expressed in the hadronic center-of-mass system (c.m.s.) and $q^0 = (q^{*2} - Q^2)^{1/2}$. Here we use a right-handed coordinate system where the z axis is in the direction of $\vec{q}$ and the y axis is parallel to $(\vec{q} \times \vec{q}\,')$.

The interference between the Deck graph [Fig. 1(c)] and the resonant graph [Fig. 1(b)] leads to the following expressions:

$$\begin{aligned}\sigma_U = \mathfrak{N}\,\mathrm{Re}(A_1^1 \mathfrak{B}\mathfrak{D}^*)\Bigg\{ & G_1(m_A g_s)\left(1 + \cos\theta + \frac{r_1}{m_\rho^{\,2}}\right) + \frac{g_d}{4m_A}\,G_2\,\frac{r_1}{2}\left[t - t_1 - m_\pi^{\,2} - \frac{1}{2m_\rho^{\,2}}(M_A^{\,2} - m_\rho^{\,2} - m_\pi^{\,2})(Q^2 + t_1 + m_\rho^{\,2})\right] \\ & + (m_A g_s)G_2\left[q_1^x[q_1^x\cos\theta + (q^* - q_1^z)\sin\theta] + (q_1^y)^2 - \frac{r_1}{2m_\rho^{\,2}}(Q^2 + t_1 + m_\rho^{\,2})\right] \\ & + G_1\,\frac{g_d}{4m_A}\left[-q_2^x(\cos\theta\, q_1^x - q_1^z\sin\theta) - q_1^y q_2^y + \frac{r_1}{2m_\rho^{\,2}}(M_A^{\,2} - m_\rho^{\,2} - m_\pi^{\,2})\right]\Bigg\},\end{aligned}$$

$$\begin{aligned}\sigma_L = -\frac{2}{m_A\sqrt{Q^2}}\,\mathfrak{N}\,\mathrm{Re}(A_0^0 \mathfrak{B}\mathfrak{D}^*)\Bigg\{ & G_1(m_A g_s)\left(-q^* q'^* + q^0 q'^0\cos\theta + \frac{r_2}{m_\rho^{\,2}}\right) \\ & + \frac{g_d}{4m_A}\,G_2\,\frac{r_2}{2}\left[t - t_1 - m_\pi^{\,2} - \frac{1}{2m_\rho^{\,2}}(M_A^{\,2} - m_\rho^{\,2} - m_\pi^{\,2})(Q^2 + t_1 + m_\rho^{\,2})\right] \\ & - G_2(m_A g_s)\left[(q^* q_1^0 - q^0 q_1^z)[q'^*(q^0 - q_1^0) - q'^0(-q_1^x\sin\theta + (q^* - q_1^z)\cos\theta)] + \frac{r_2}{2m_\rho^{\,2}}(Q^2 + t_1 + m_\rho^{\,2})\right] \\ & + G_1\,\frac{g_d}{4m_A}\left[-(q^* q_2^0 - q^0 q_2^z)[q'^* q_1^0 - q'^0(q_1^x\sin\theta + q_1^z\cos\theta)] + \frac{r_2}{2m_\rho^{\,2}}(M_A^{\,2} - m_\rho^{\,2} - m_\pi^{\,2})\right]\Bigg\},\end{aligned}$$

with

$$r_1 = (\cos\theta\, q_1^x - q_1^z\sin\theta)q_1^x + (q_1^y)^2,$$

$$r_2 = [q'^* q_1^0 - q'^0(q_1^x\sin\theta + q_1^z\cos\theta)](q^* q_1^0 - q^0 q_1^z),$$

$$\mathfrak{B} = \frac{1}{q'^2 - m_A^{\,2} + i m_A \Gamma}\,.$$

Here q'^* is the momentum of q' in the hadronic c.m.s., and $q'^0 = [(q'^*)^2 + M_A^{\,2}]^{1/2}$. The components of q_2 are also expressed in this system. The angle θ is the hadronic-c.m.s. scattering angle for the production of a $(\rho\pi)$ system with the four momentum q' and the mass M_A.

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