Exclusive neutrino-induced production of pseudoscalar mesons in the neutral currents

Yu. Ya. Komachenko and M. Yu. Khlopov

Institute of High Energy Physics, Serpukhov
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A study is made of exclusive processes of production of the pseudoscalar π^0, η, and η' mesons in the weak neutral currents, due to scattering of a neutrino: a) by virtual mesons (Reggeons) at the periphery of a nucleon; b) in the Coulomb field of a proton (nucleus). The study of such processes will make it possible to obtain information about the weak transitions meson (Reggeon) $\rightarrow \pi^0(\eta,\eta')$ and about the effects of the isoscalar axial current.

1. INTRODUCTION

The development of neutrino physics at high energies offers hope that it will be possible to investigate in detail exclusive processes of neutrino-induced production of pseudoscalar mesons:

$$\nu N \rightarrow \nu P^0 N. \tag{1}$$

The study of this reaction involving production of single neutral (and also charged) pions at the threshold made it possible as early as the mid-seventies to determine the coupling constant of the weak neutral hadron currents and thereby to test the Weinberg–Salam model. Experimental and theoretical investigations of the reaction (1) (and also of the reaction $\nu N \rightarrow \mu\pi N$ in the charged currents) for invariant masses of the πN system in the range $M_{\pi N} < 2$ GeV revealed the importance of the contribution to this process from baryon resonances.[1–5] However, at small momentum transfers to the nucleon there can also be a contribution to the reaction (1) from other mechanisms, whose analysis is of interest. In the present paper, we carry out such an analysis in the framework of an approach which we proposed previously[6] for the description of exclusive peripheral neutrino processes. It is assumed in this approach that the reaction (1) is caused by scattering of a neutrino by virtual mesons (Reggeons) at the periphery of the nucleon (see Fig. 1). If the process (1) takes place on nuclei, there can be a coherent enhancement due to scattering of the neutrino by virtual isoscalar mesons. Diffractive coherent production of single π^0 mesons in the neutral currents was discussed in Ref. 7. In the present paper, we consider processes of scattering of a neutrino by all possible virtual mesons and Reggeons. Our analysis shows that, besides the reaction $\nu N \rightarrow \mu\pi N$ discussed previously, a study of the process (1) with $P^0 = \pi^0$, η, η' could provide important information about the structure of the periphery of the nucleon.

There is also a contribution to the reaction (1) from the diagram of Fig. 2, corresponding to an effect analogous to the Primakoff effect.[8] With decrease of the momentum transferred to the nucleon, the contribution of this diagram to the cross section for the process (1) at high energies can become dominant. Consequently, just as the Primakoff effect in photoproduction provides the most reliable information about the $P^0 \rightarrow 2\gamma$ decay probability, an investigation of the reaction (1) would make it possible to study the unobservable weak decays

$$P^0 \rightarrow \nu\bar{\nu}\gamma. \tag{2}$$

A similar effect in the charged currents was considered in Refs. 9 and 10. The process (1) due to the contribution of the diagram in Fig. 2 is a weak–electromagnetic process, as is the previously considered[11] process

$$\nu N \rightarrow \nu\gamma N. \tag{3}$$

Unlike the reaction (3), determined by the two-current nucleon amplitudes, the contribution of the diagram in Fig. 2 to the process (1) is determined by the two-current meson amplitudes of the decay (2). Separation of the contributions of the diagrams in Figs. 1 and 2 will make it possible to obtain information about the form factors of the transitions (2) and

$$M(R) \rightarrow P^0\nu\bar{\nu}. \tag{4}$$

As we shall show in the present paper, this possibility of studying the unobservable decays (2) and (4) due to the neutral currents could in principle make it possible to obtain important information about the structure of the weak neutral hadron current (in particular, about the presence of the isoscalar axial current) and about the violation of $SU_f(N)$ symmetry.

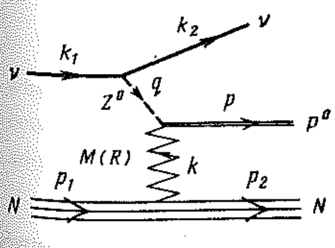

FIG. 1.

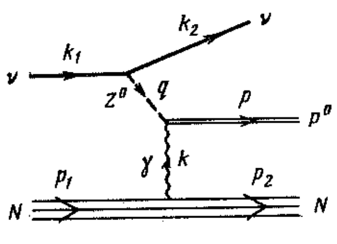

FIG. 2.

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2. AMPLITUDES FOR NEUTRINO-INDUCED PRODUCTION OF PSEUDOSCALAR MESONS

Let us consider the process of neutrino-induced production of a P^0 meson by the neutral current, described by the diagrams of Figs. 1 and 2. In the figures, k_1 and k_2 are the neutrino momenta, p_1 and p_2 are the momenta of the nucleon before and after the collision, p is the meson momentum, and we have introduced the invariants $s=(k_1+p_1)^2$, $s_1=(p+p_2)^2$, $s_2=(p+k_2)^2$, $t_1=(p_1-p_2)^2=k^2$, $t_2=(k_1-k_2)^2=q^2$. The matrix element corresponding to these diagrams has the form

$$M=M^h+M^\gamma=\frac{G}{\sqrt{2}}l_\mu(H_\mu^h+H_\mu^\gamma). \tag{5}$$

In Eq. (5), $l_\mu=\bar{\nu}_2\gamma_\mu(1+\gamma_5)\nu_1$ is the lepton current and H_μ^h is the weak hadron current corresponding to the diagram of Fig. 1, which can be represented in the form

$$H_\mu^h=V_\mu^h+A_\mu^h=\sum_{M_i}T^{(M_i)}P^{(M_i)}\langle P^0|V_\mu|M_i\rangle + \sum_{M_j\neq M_i}T^{(M_j)}P^{(M_j)}\langle P^0|A_\mu|M_j\rangle. \tag{6}$$

Here $T^{(M_i)}$, $T^{(M_j)}$, $P^{(M_i)}$, $P^{(M_j)}$ are, respectively, the meson–nucleon vertices and the propagators of the virtual mesons M_i and M_j, and $\langle P^0|V_\mu|M_i\rangle$ and $\langle P^0|A_\mu|M_j\rangle$ are the matrix elements of the weak hadron vector and axial currents between the states of the virtual mesons M_i and M_j and the pseudoscalar P^0 meson. We note that for large invariant masses of the P^0N system the virtual meson is Reggeized, and the Pomeron contribution is added to the amplitude (5).

The current H_μ^γ corresponding to the diagram of Fig. 2 has the form

$$H_\mu^\gamma=e(\bar{u}_2\gamma_\nu u_1)k^{-2}T_{\mu\nu}(k^2,q^2), \tag{7}$$

where

$$T_{\mu\nu}(k^2,q^2) =\iint\langle P^0|T[J_\mu^W(x),J_\nu^{EM}(y)]|0\rangle\exp(iqx+iky)\,d^4x\,d^4y =ef_P(k^2,q^2)\,\varepsilon_{\mu\nu\lambda\rho}q_\lambda k_\rho \tag{8}$$

is the $P^0Z\gamma$ weak–electromagnetic vertex. In accordance with the results of Ref. 6, we shall take into account the contribution to the diagram of Fig. 1 from only the ω, ρ, f, A_1, and A_2 mesons[1)] and the Pomeron. According to the C-parity selection rules, the transitions $\omega\to P^0$ and $\rho\to P^0$ are due to the weak vector current, and the transitions $f\to P^0$, $A_1^0\to P^0$, $A_2^0\to P^0$, $h\to P^0$, $P\to P^0$ are due to the axial current.

The combined action of the C- and P-parity selection rules forbids the transitions $\pi^0\to P^0$ and $\eta(\eta')\to P^0$.

We note that according to the C- and G-parity selection rules the transitions $A_1^0\to\pi^0$, $A_2^0\to\pi^0$, $f\to\eta(\eta')$, $h\to\eta(\eta')$, $P\to\eta(\eta')$ are due to the isoscalar axial current, which is absent for the u and d quarks in the Weinberg–Salam model. Since the axial current of the s quark is isoscalar, the isoscalar axial transitions $f\to\eta(\eta')$, $h\to\eta(\eta')$, $P\to\eta(\eta')$ can take place as the result of the admixture of strange quarks in the f and h mesons and in the Pomeron. This admixture of s quarks in the wave functions of the isovector A_1^0, A_2^0, and π^0 mesons is small, and therefore the contribution of the transitions $A_1^0\to\pi^0$ and $A_2^0\to\pi^0$ can be neglected.

A. Amplitudes of the hadron vector current

In the most general form, the amplitude of the hadron vector current has the structure

$$V_\mu^h=\sum_{M=\omega,\rho}\Phi_{MP^0}(s_1,k^2,q^2)(\bar{u}_2\gamma_\nu u_1)\,\varepsilon_{\mu\nu\lambda\rho}q_\lambda k_\rho, \tag{9}$$

where $\Phi_{MP^0}(s_1,k^2,q^2)$ are the invariant amplitudes corresponding to scattering of a neutrino by virtual ω and ρ mesons. Taking into account the fact that the weak neutral vector current in the Weinberg–Salam model has the form $V_\mu=V_\mu^3-2\sin^2\theta_W(V_\mu^3+V_\mu^S)$, where V_μ^3 and V_μ^S are, respectively, the isovector and isoscalar parts, and using the CVC hypothesis and the G-parity selection rule, it is possible to obtain relations between the weak amplitudes $\Phi_{MP^0}(s_1,k^2,q^2)$ at $q^2=0$ and the invariant amplitudes $\Phi_{\gamma P^0}^M(s_1,k^2)$ for the photoproduction processes, whose amplitudes $A^{\gamma N\to P^0N}$ are

$$A^{\gamma N\to P^0N}=\sum_M\Phi_{\gamma P^0}^M(s_1,k^2)\,e_\mu^\gamma(\bar{u}_2\gamma_\nu u_1)\,\varepsilon_{\mu\nu\lambda\rho}q_\lambda k_\rho. \tag{10}$$

For the various mesons, we obtain the relations

$$\Phi_{\omega\pi^0}(s_1,k^2,q^2=0)=\frac{1-2\sin^2\theta_W}{e}\Phi_{\gamma\pi^0}^{\omega}(s_1,k^2),$$
$$\Phi_{\rho\pi^0}(s_1,k^2,q^2=0)=\frac{-2\sin^2\theta_W}{e}\Phi_{\gamma\pi^0}^{\rho}(s_1,k^2), \tag{11a}$$
$$\Phi_{\omega\eta(\eta')}(s_1,k^2,q^2=0)=\frac{-2\sin^2\theta_W}{e}\Phi_{\gamma\eta(\eta')}^{\omega}(s_1,k^2)$$
$$\Phi_{\rho\eta(\eta')}(s_1,k^2,q^2=0)=\frac{1-2\sin^2\theta_W}{e}\Phi_{\gamma\eta(\eta')}^{\rho}(s_1,k^2), \tag{11b}$$

which hold in all regions of the invariant masses of the hadronic P^0N system: both in the region $s_1=s_{P^0N}<s_M$, in which we are dealing with scattering by a virtual meson (the meson region), and in the region $s_1>s_R$, in which the scattering takes place on a virtual Reggeon (the Regge region). Here s_M and s_R are parameters which determine the transition to the Regge asymptotic behavior, for which in obtaining estimates we shall take $s_M\sim s_R\sim$ 15–20 GeV^2 (see Refs. 6, 11, and 12). In the meson region, the invariant amplitudes $\Phi_{\gamma P^0}^M(s_1,k^2)$ do not depend on s_1 and for small k^2 have the form

$$\Phi_{\gamma P^0}^M(k^2)=\frac{g_{MN}g_{MP^0\gamma}}{k^2-m_M^2}. \tag{12}$$

Here g_{MN} are the meson–nucleon coupling constants, for which in obtaining estimates we shall take $g_{\rho N}^2/4\pi=0.68$ and $g_{\omega N}/4\pi=21.5$,[13] and $g_{MP^0\gamma}$ are the coupling constants of the weak–electromagnetic decays $M\to P^0\gamma$ (or $P^0\to M\gamma$), which are related to the corresponding widths as follows:

$$\Gamma_{M\to\pi^0(\eta)\gamma}=\frac{g^2_{M\pi^0(\eta)\gamma}[m_M^2-m^2_{\pi^0(\eta)}]^3}{96\pi m_M^3},$$

$$\Gamma_{\eta'\to M\gamma}=\frac{g^2_{\eta' M\gamma}[m^2_{\eta'}-m_M^2]^3}{32\pi m_{\eta'}^3}.$$

We note that the quark model establishes relations between the meson–nucleon coupling constants and the constants of the electromagnetic decays $M \to P^0\gamma(P^0 \to M\gamma)$: $g_{\omega p} = 3g_{\rho p}$, $g_{\omega N} = -3g_{\rho N}$, $g_{\omega\pi\gamma} = 3g_{\rho\pi\gamma}$, $g_{\omega\eta\gamma} = (1/3)g_{\rho\eta\gamma}$, $g_{\eta'\omega\gamma} = (1/3)g_{\eta'\rho\gamma}$. These relations lead to a suppression of the contribution of the vector current to the processes $\nu p \to \nu\eta(\eta')p$, since by taking into account the approximate equality of the ω- and ρ-meson masses we obtain

$$\Phi_{\omega\eta(\eta')}(k^2, q^2=0) + \Phi_{\rho\eta(\eta')}(k^2, q^2=0)$$

$$= \frac{g_{\omega p} g_{\omega\eta(\eta')\gamma}}{k^2 - m_\omega^2} \frac{(1 - 4\sin^2\theta_W)}{e},$$

and $\sin^2\theta_W$ is close to 1/4.

It is interesting that different relations between the constants $g_{\omega N}$ and $g_{\rho N}$ are obtained from the quark model and from phenomenological analysis of the NN interaction potentials in OBEP models.[13] This discrepancy may be due to the contribution from the interaction of the isoscalar ω meson with the quark sea, which is not taken into account in our approximation of valence quarks.

In the Regge region, the amplitudes of the vector current, which determine the corresponding photoproduction amplitudes [see (11a) and (11b)], fall off with increase of the invariant mass of the P^0N system as $1/\sqrt{s_1}$. This leads to a suppression of the contribution from the Regge region to the differential and total cross sections of the vector current (see Sec. 3).

B. Amplitudes of the axial hadron current

In the meson region, the amplitude of the weak axial hadron current due to scattering of the neutrino by virtual f and A_2 mesons has the form[2)]

$$A_\mu^h = \sum_{M=f,A_2} \frac{g_{MN}(\bar{u}_2\gamma_\nu u_1)(p_1+p_2)_\lambda}{k^2 - m_M^2}$$

$$\times P_{\sigma\tau}^{\nu\lambda}\{f_{1M}^{P^0}(k^2, q^2)(g_{\mu\sigma}q_\tau + g_{\mu\tau}q_\sigma)$$

$$+ [f_{2M}^{P^0}(k^2, q^2)k_\mu + f_{3M}^{P^0}(k^2, q^2)q_\mu]q_\sigma q_\tau\}. \qquad (13)$$

In Eq. (13), g_{MN} are the meson–nucleon coupling constants, for which we shall take $g_{fN}/4\pi^2 = 3.7\ \mathrm{GeV}^{-2}$ (according to the estimates of Ref. 6) and $g_{A_2N} = (1/3)g_{fN}$ (from the quark model), $P_{\sigma\tau}^{\nu\lambda}$ is the polarization operator of the tensor 2^+ meson (see Refs. 6 and 14), and $f_{1,2,3M}^{P^0}$ are the form factors of the weak transitions $M \to P^0$. We shall neglect their variation as the meson M goes off the mass shell and assume that $f_{1,2,3M}(k^2, q^2) \approx f_{1,2,3M}(m_M^2, q^2) \approx f_{1,2,3M}(0, q^2)$. The PCAC hypothesis makes it possible to relate the values of the form factors for the transitions $f \to \pi_0$ and $A_2^0 \to \eta(\eta')$ due to the axial isovector current, $f_{1f}^{\pi^0}(q^2)$ and $f_{1A_2}^{\eta(\eta')}(q^2)$, at $q^2 = 0$ to the constants of the strong decays $f \to 2\pi^0$ and $A_2^0 \to \eta\pi^0(A_2^0 \to \eta'\pi^0)$. This relation has the form

$$f_{1f}^{\pi^0}(0) = \sqrt{2} f_\pi g_{f\pi^0\pi^0}, \qquad f_{1A_2}^{\eta(\eta')}(0) = \sqrt{2} f_\pi g_{A_2^0\eta(\eta')\pi^0}, \qquad (14)$$

where $f_\pi \approx 132$ MeV is the $\pi \to \mu\nu$ decay constant, and the constants $g_{f\pi^0\pi^0}$ and $g_{A_2^0\eta\pi^0}$ are related as follows to the widths of the corresponding decays:

$$\frac{g_{f\pi^0\pi^0}^2}{4\pi} = \frac{15\Gamma_{f\to 2\pi^0}}{m_f^3(1 - 4m_\pi^2/m_f^2)^{5/2}} = \frac{1}{4}\frac{g_{f\pi^+\pi^-}^2}{4\pi}$$

$$= 0.425 \pm 0.050\ \mathrm{GeV}^{-2}, \qquad (15)$$

$$\frac{g_{A_2^0\eta\pi^0}^2}{4\pi} = \frac{30\Gamma_{A_2\to\eta\pi^0}}{m_{A_2}^3(1 - m_\eta^2/m_{A_2}^2)^5} = 0.57 \pm 0.07\ \mathrm{GeV}^{-2}. \qquad (16)$$

From the experimental limit on the width of the decay $A_2 \to \eta'\pi$ ($\Gamma_{A_2\to\eta'\pi} < 2.3$ MeV),[15] we obtain $g_{A_2\eta'\pi}^2/4\pi < 1\ \mathrm{GeV}^{-2}$. The contribution of the form factor $f_{2M}^{P^0}$ to the cross section for the process (1) is small at small momentum transfers to the nucleon. The contribution of the form factor $f_{3M}^{P^0}$ vanishes, since $q_\mu l_\mu = 0$ (for the neutral current). An estimate of the values of the form factors for the transitions $f \to \eta(\eta^{2\prime})$ at $q = 0$ in the quark model gives

$$[f_{1f}^{\eta(\eta')}(0)]^2 = \alpha_{s\bar{s}}^f \delta_{\eta(\eta')s}[f_{1f}^{\pi^0}(0)]^2, \qquad (17)$$

where $\alpha_{s\bar{s}}^f$ is the fraction of strange quarks in the f meson. The factor $\delta_{\eta(\eta')s} = 2/3(1/3)$ arises from the wave function of the η (η') meson. The value of $\alpha_{s\bar{s}}^f$ can be obtained from an estimate of the nonideal mixing[16] in the nonet of tensor mesons: $\alpha_{s\bar{s}}^f = \sin^2\theta_f = \sin^2 5.6° \approx (0.0976)^2$

In view of the possible existence of an isoscalar axial current of the u and d quarks due to exchange of a new Z'boson, as predicted, for example, in the phenomenology of superstring models,[17] we shall estimate the contribution of such a current to the amplitude for the weak transition $f \to \eta$. On the basis of the generalized PCAC hypothesis for the η meson, it is possible to obtain the relation

$$f_{1f}^{(u,d)}(0) = 2x f_\eta^{u,d} g_{f\eta\eta}, \qquad (18)$$

where $f_\eta^{u,d} = f_\pi$; the constant $g_{f\eta\eta}$ is determined from experimental data on the decay $f \to \eta\eta$ (Ref. 18) and has the value

$$\frac{g_{f\eta\eta}^2}{4\pi} = \frac{15\Gamma_{f\to\eta\eta}}{m_f^3(1 - 4m_\eta^2/m_f^2)^{5/2}} \approx 0.12\ \mathrm{GeV}^{-2},$$

and the quantity $x \propto (m_Z/m_{Z'})^2$ characterizes the suppression of the transition $\nu f \to \nu\eta$ due to the mass of the Z' boson. Comparing (17) and (18), we find that for

$$x > \frac{g_{f\pi^0\pi^0}}{g_{f\eta\eta}} \frac{(2\alpha_{s\bar{s}}^f \delta_{\eta s})^{1/2}}{2} = 0.34$$

the contribution of the interaction due to exchange of the Z' boson dominates in the weak transition $\nu f \to \nu\eta$.

In the Regge region, the process (1) with π^0 production is due to exchanges of the f trajectory and the Pomeron. The corresponding current (for small momentum transfers $\sqrt{|k|^2} \ll M_N$ to the nucleon, where M_N is the nucleon mass) has the form

$$A_\mu^h = F_A^\pi(s_1, k^2, q^2)(p_1 + p_2)_\mu. \qquad (19)$$

According to the results of Ref. 6, the invariant amplitude $F_A(s_1, k^2, q^2)$ is related at $q^2 = 0$ through the PCAC relation to the amplitude for elastic $\pi^0 N$ scattering:

$$F_A^\pi = \frac{f_\pi}{\sqrt{2}s_1} T_{\pi^0N}. \qquad (20)$$

The amplitude T_{π^0N} is normalized so that

$$\frac{d\sigma^{\pi^0N\to\pi^0N}}{d|t_1|} = 4\pi\left|\frac{T_{\pi^0N}}{16\pi p(s_1)\sqrt{s_1}}\right|^2, \qquad (21)$$

where

$$p(s_1) = {}^1/_2 s_1^{-1/2}[s_1^2 - 2s_1(M_N^2 + \mu_P^2) + (M_N^2 - \mu_P^2)^2]^{1/2},$$

in which μ_p is the mass of the P^0 meson.

The process (1) with production of η and η' is determined in the Regge region by the contributions of the A_2 and f trajectories and the Pomeron. The contribution of the A_2 trajectory can be related by means of the PCAC relation to the amplitude for the charge-exchange process $\pi^- p \to \eta(\eta')n$:

$$F_{A_2}^{\eta(\eta')} = \frac{f_\pi}{\sqrt{2}\, s_1} T_{\pi^0 N \to \eta(\eta')N} = \frac{f_\pi}{2 s_1} T_{\pi^- p \to \eta(\eta')n}. \tag{22}$$

The amplitude for the process (1) in the case $\nu N \to \nu\eta(\eta')N$ due to exchange of the Pomeron and the f trajectory can be related by means of the PCAC hypothesis, generalized (see Ref. 19) to the case of the isoscalar axial current, to the amplitude $T_{\eta_s N \to \eta_s N}$ for scattering of the pseudoscalar $s\bar{s}$ state by the nucleon,

$$F_{f+P}^{\eta(\eta')} = s_1^{-1} f_{\eta(\eta')s} \delta_{\eta(\eta')s}^{1/2} T_{\eta_s N}, \tag{23}$$

where $f_{\eta(\eta')s}$ is defined (see Ref. 19) as

$$f_{\eta(\eta')s} = \frac{2m_s}{g_{\eta(\eta')s\bar{s}}}, \tag{24}$$

and the amplitude $T_{\eta_s N}$ is related by means of the quark model to the $\pi^0 N \to \pi^0 N$ scattering amplitude due to the P and f exchanges:

$$T_{\eta_s N} = \frac{m_u}{m_s} T_{\pi^0 N}. \tag{25}$$

Since

$$\left| \frac{f_\pi}{2} T_{\pi^- p \to \eta(\eta')n} \right| \ll \left| \frac{2m_\pi}{g_{\eta(\eta')s\bar{s}}} T_{\pi^0 N} \right|,$$

the contribution of the A_2 trajectory can be neglected in the Regge region.

3. DIFFERENTIAL CROSS SECTION FOR THE PROCESS. ESTIMATE OF THE TOTAL CROSS SECTIONS

The differential cross section for the reaction (1) has the form

$$\frac{d^4\sigma}{dk^2\, dq^2\, ds_2\, d\varphi} = \frac{\overline{|M|^2}}{(2\pi)^4 \cdot 32 (s-M_N^2)^2 (s_2 - k^2)}, \tag{26}$$

where φ is the Treiman–Yang azimuthal angle.

If the momentum of the recoil nucleon is small, $|\mathbf{p}_2| \leqslant \alpha M_N$ ($\alpha \ll 1$) (in this case, $|k^2| \leqslant \alpha^2 M_N^2$), the variables q^2, s_2, and k^2 vary in the ranges (for $E_\nu \gg \alpha M_N$, $E_\nu \gg \mu_P^2/2M_N$, where E_ν is the energy of the incident neutrino in the laboratory system)

$$0 \leqslant |q^2| \leqslant s_2 - \mu_P^2, \qquad \mu_P^2 \leqslant s_2 \leqslant \frac{s-M_N^2}{M_N} \sqrt{|k^2|} = 2E_\nu \sqrt{|k^2|},$$

$$\frac{\mu_P^4}{4E_\nu^2} \leqslant |k^2| \leqslant \alpha^2 M_N^2.$$

We note that the invariant $s_1 = (p_1 + q)^2$ is related linearly to the cosine of the angle φ: $s_1 = s_{10} + s_{1\varphi} \cos\varphi$. For $\alpha \ll 1$, $E_\nu \gg \alpha M_N$, the functions s_{10} and $s_{1\varphi}$ have the form

$$s_{10} = (s - M_N^2)(\mu_P^2 - q^2)/s_2 + M_N^2 + q^2, \tag{27a}$$

$$s_{1\varphi} = -\frac{2}{s_2} \left\{ [(s-M_N^2)^2 k^2 + s_2^2 M_N^2] q^2 \left(1 - \frac{\mu_P^2 - q^2}{s_2}\right) \right\}^{1/2}. \tag{27b}$$

After an integration with respect to the Treiman–Yang angle, we obtain in the meson region the following expression for the differential cross section of the process (1) (Figs. 1 and 2) due to the vector current:

$$\frac{d^3\sigma^V}{dk^2\, dq^2\, ds_2} = \frac{1}{(2\pi)^3 \cdot 32 (s-M_N^2)^2 s_2} \frac{G^2}{2} \Big[\frac{e^2 f_P(q^2)}{k^2} + \Phi_{\omega P^0}(k^2, q^2) + \Phi_{\rho P^0}(k^2, q^2) \Big]^2 \cdot 4q^2 [k^2 (s-M_N^2)^2 + s_2^2 M_N^2][2 - 2(\mu_P^2 - q^2)/s_2 + (\mu_P^2 - q^2)^2/s_2^2]. \tag{28}$$

It can be seen from this that for neutrino energies

$$E_\nu^2 > \frac{\mu_P^4}{4e^2 |f_P(q^2)|} \Big| \sum_M \Phi_{MP^0}(k^2, q^2) \Big|$$

with $k^2 = k^2_{\min}$ the contribution from the diagram of Fig. 2 is dominant in the differential cross section. Assuming the same q^2 dependence of the form factors of $f_P(q^2)$ and $\Phi_{MP^0}(q^2)$ and using the numerical values of $\Phi_{MP^0}(0)$, and $f_P(0)$ (see Sec. 2A and Ref. 19), we find that diagram 2 is dominant in the differential cross section for neutrino energies $E_\nu > 1.7$ GeV in the case of π^0-meson production, $E_\nu \gtrsim 3.3$ GeV for η production, and $E_\nu \gtrsim 7$ GeV for η'-meson production (for the estimates, we have taken the value $\sin^2\theta_W = 0.23$).

In the Regge region, where the contribution of diagram 1 is suppressed, we can confine ourselves to the contribution of diagram 2:

$$\frac{d^3\sigma^V}{dk^2\, dq^2\, ds_2} = \frac{1}{(2\pi)^3 \cdot 32 (s-M_N^2)^2 s_2} \frac{G^2}{2} \left[\frac{e^2 f_P(q^2)}{k^2} \right]^2 \times 4q^2 [k^2 (s-M_N^2)^2 + s_2^2 M_N^2] \left[2 - 2\left(\frac{\mu_P^2 - q^2}{s_2}\right) + \left(\frac{\mu_P^2 - q^2}{s_2}\right)^2 \right]. \tag{29}$$

Assuming for all the form factors (f_P, Φ_{MP^0}) a universal q^2 dependence of the form

$$f(q^2) = f(0)/(1 - q^2/\Lambda^2), \tag{30}$$

where $\Lambda^2 \approx 1$ GeV^2, we obtain at high energies ($s \gg M_N^2$; $\alpha s \gg \Lambda^2, \mu_P^2$; $\alpha S_M \gg \Lambda^2, \mu_P^2$) and small momentum transfers to the nucleon, $|k^2| \ll m_M^2, M_N^2$, the total cross sections corresponding to the meson (Fig. 1) and Coulomb (Fig. 2) mechanisms:

$$\sigma_{P^0}^{\omega+\rho} = \frac{G^2 \Lambda^4}{16(2\pi)^3} [\Phi_{\omega P^0}(0,0) + \Phi_{\rho P^0}(0,0)]^2 \frac{\alpha^4 M_N^4}{4} \times \left[\ln^2\left(1 + \frac{\alpha s_M}{\Lambda^2}\right) - \frac{3}{2} \ln\left(1 + \frac{\alpha s_M}{\Lambda^2}\right) + \frac{1}{8} \right], \tag{31}$$

$$\sigma_{P^0}^{\gamma} = \frac{G^2 \Lambda^4}{16(2\pi)^3} [e^2 f_P(0)]^2 \left[\frac{2}{3} \ln^3 \frac{\alpha s}{\Lambda^2} - \ln^2 \frac{\alpha s}{\Lambda^2} \right]. \tag{32}$$

For $s = 200$ GeV^2, $s_M = 15$ GeV^2, $\alpha = 1/4$, and $\sin^2\theta_W = 0.23$, we have the following individual contributions:

$$\sigma_{\pi^0}^{\omega+\rho} \simeq 6 \cdot 10^{-42}\ \text{cm}^2, \qquad \sigma_\eta^{\omega+\rho} \simeq 6 \cdot 10^{-44}\ \text{cm}^2,$$

$$\sigma_{\eta'}^{\omega+\rho} \simeq 10^{-43}\ \text{cm}^2, \qquad \sigma_{\pi^0}^{\gamma} \simeq 3 \cdot 10^{-46}\ \text{cm}^2,$$

$$\sigma_\eta^{\gamma} \simeq 4 \cdot 10^{-45}\ \text{cm}^2, \qquad \sigma_{\eta'} \simeq 10^{-43}\ \text{cm}^2.$$

The differential cross section for the process (1) due to the axial current has the following form:

a) in the meson region [for $\alpha \ll 1$, $E_\nu \gg \alpha M_N$ (in this case, $s_{10} \gg s_{1\varphi}$; $|k^2| \ll m_M^2, M_N^2$)]

$$\frac{d^3\sigma^A}{dk^2\,dq^2\,ds_2}=\frac{G^2}{(2\pi)^3 s_2}\left(1-\frac{\mu_P{}^2-q^2}{s_2}\right)\left[\frac{g_{fN}f_{1f}{}^P(q^2)}{m_f{}^2}+\frac{g_{A_2N}f^P_{1A_2}(q^2)}{m_{A_2}{}^2}\right]^2(s-M_N{}^2)^2\left(\frac{\mu_P{}^2-q^2}{s_2}\right)^2, \qquad (33)$$

where in the case of π^0 production we neglect the A_2 contribution (see Sec. 2);

b) in the Regge region

$$\frac{d^3\sigma^A}{dk^2\,dq^2\,ds_2}=\frac{G^2}{(2\pi)^3 4s_2}\left(1-\frac{\mu_P{}^2-q^2}{s_2}\right)|F_A{}^P|^2, \qquad (34)$$

where the quantities F^P_A are determined by Eqs. (20)–(25).

Comparison of the differential cross sections (28), (29) and (33), (34) indicates the fundamental possibility that the peak at $k^2 = 2k^2_{\min}$ in the differential cross section due to the Coulomb mechanism (Fig. 2) can be separated in the meson region for

$$|q^2|<[e^2f_P(0)]^2\Big/\left[\left(\sum_M\frac{g_{MN}f^P_{1M}(0)}{m_M{}^2}\right)^2 32m_N{}^2\right]$$

and in the Regge region for

$$|q^2|>\frac{2|F_A{}^P(0)|^2\,|k^2_{min}|}{[e^2f_P(0)]^2}.$$

Under the assumption that the q^2 dependence of all the form factors has the form (30), we find that the total cross section for the reaction (1) due to the axial current has the following form in the meson region (in the limit $E_\nu \gg \alpha M_N, \alpha s_M \gg \mu_P^2$):

$$\sigma_{P^0}{}^M=\frac{G^2M_N{}^2}{(2\pi)^3}\left[\frac{g_{fN}f_{1f}{}^P(0)}{m_f{}^2}+\frac{g_{A_2N}f^P_{1A_2}(0)}{m_{A_2}{}^2}\right]^2$$
$$\times\Bigg\{\frac{\alpha^2\Lambda^2 s_M{}^2}{2}\left(1-\frac{s_M}{s}\right)$$
$$-2\alpha\Lambda^4 s_M\left(1-\frac{s_M}{2s}\right)+2\Lambda^6\Bigg[F_{\text{Sp}}\left(\frac{\alpha s_M}{\Lambda^2}\right)-\frac{s_M}{s}\Bigg[\left(\frac{\Lambda^2}{\alpha s_M}+1\right)$$
$$\times\ln\left(1+\frac{\alpha s_M}{\Lambda^2}\right)-1\Bigg]\Bigg]\Bigg\}. \qquad (35)$$

Here $F_{\text{Sp}}(\xi) = \int_0^\xi [\ln(1+x)/x]\,dx$ is the Spence function. For $s \gg s_M$, $s_M = 10\ \text{GeV}^2$, $\Lambda^2 = 1\ \text{GeV}^2$, and $\alpha = 1/4$, we obtain $\sigma^M_{\pi^0} \simeq 0.9\times10^{-39}$ cm^2, $\sigma^M_\eta \simeq 1.7\times10^{-40}$ cm^2, $\sigma^M_{\eta'} < 2.5\times10^{-40}$ cm^2.[3)] If $s < s_M$ in (35), it is necessary to make the substitution $s_M \to s$. It can be seen from Eq. (35) that the total cross section becomes much smaller at lower energies; for example, for $s = s_M = 10\ \text{GeV}^2$ the cross section for π^0-meson production is $\sigma^M_{\pi^0}(s=s_M) \simeq 2\times10^{-40}$ cm^2. In the Regge region, the total cross section has the form

$$\sigma_{\pi^0}{}^R=\frac{G^2M_N{}^2}{4(2\pi)^3}\alpha^2\Lambda^2\frac{f_\pi{}^2(\sigma^{\pi N}_{tot})^2}{2}\left(\ln\frac{s}{s_R}-1\right), \qquad (36a)$$

$$\sigma_{\eta'}{}^R=\frac{G^2M_N{}^2}{4(2\pi)^3}\alpha^2\Lambda^2 f^2_{\eta(\eta')_s}\delta_{\eta(\eta')_s}(\sigma^{\eta_sN}_{tot})^2\left(\ln\frac{s}{s_R}-1\right) \qquad (36b)$$

and for $s = 200\ \text{GeV}^2$ $s_R = 20\ \text{GeV}^2$ $\alpha = 1/4$ we obtain $\sigma^R_{\pi^0} \simeq 1.2\times10^{-40}$ cm^2, $\sigma^R_\eta \simeq 1.2\times10^{-40}$ cm^2, $\sigma^R_{\eta'} \simeq 10^{-40}$ cm^2.

4. EFFECTS OF MESONS WITH HIGHER SPINS

In the approach which we have developed, an important role is played by the idea that there exists a region of invariant masses of the P^0N system in which the reaction (1) is due to exchange of virtual mesons. Then t-channel exchange of a meson with spin l gives a contribution to the amplitude for the reaction (1) proportional to ss_1^{l-1}. The corresponding contribution to the total cross section (see Sec. 3) is determined by the upper limit of the meson region, s_M. When the contribution of the mesons with higher spins lying on a single Regge trajectory becomes equal to the contribution of the lowest-lying meson, there is an effective summation of their contributions, which, according to Van Hove, leads to a Regge behavior of the amplitude. At this phenomenological level of description of the amplitude for the reaction (1), the value of the parameter s_M at which the contribution of a higher-lying meson is equal to the contribution of a lower-lying meson is self-consistent.

We shall choose a self-consistent value of the quantity s_M for the dominant (see Sec. 3) contribution of the f meson by comparing its contribution to the total cross section for the process $\nu N \to \nu\pi^0 N$ with the corresponding contribution $\sigma^h_{\pi^0}$ of the $h(4^+)$ meson lying on the same trajectory as the f meson. Such a comparison (see Ref. 19) shows that for $s_M = 10\ \text{GeV}^2$, $\Lambda^2 = 1\ \text{GeV}^2$, and $\alpha = 1/4$ the total cross section is $\sigma^h_{\pi^0} \approx 10^{-39}$ cm^2, which is of the same order of magnitude as the corresponding contribution of the f meson. Thus, our phenomenological description of neutrino processes at the periphery of the nucleon is self-consistent.

We note that this result can be interpreted as follows (see Ref. 6 and the concluding section): the quantity s_M characterizes the time of formation of a virtual meson at the periphery of the nucleon, $\tau_M = 2M_N/s_M$. For interaction times $\tau < \tau_M$ (corresponding to $s_1 > s_M$), the scattering takes place on a "transient" quark–parton correlation, which can be interpreted as a Reggeon. The Regge behavior of the corresponding scattering amplitude then corresponds to the sum of the contributions of excitations with various orbital angular momenta. If the "exposure time" is $\tau = 2M_N/s_1 > \tau_M$, the excitations with higher spins are "extinguished", so that there remains the contribution of the lowest-lying meson.

5. SCATTERING ON NUCLEI

In the reaction (1) on nuclei, the cross sections due to the Coulomb mechanism (Fig. 2) and to scattering by the isoscalar mesons ω and f and by the Pomeron are coherently enhanced as $\sigma^\gamma_Z \sim Z^2\sigma^\gamma_p$ and $\sigma^M_A \sim A^2\sigma^M_N$, respectively, and the contributions of the isovector mesons are suppressed. This makes it possible to separate the contribution of the isoscalar axial current due to scattering by a virtual f meson in the case of neutrino-induced η and η' production in the meson region.

It should be noted that in the case of scattering on nuclei with large A it is important to take into account the form factor of the nucleus, $F_{\text{nuc}}(\mathbf{k}^2) = 1-(1/6)\mathbf{k}^2R^2_{\text{nuc}}$ (for $|\mathbf{k}|\,R_{\text{nuc}} \ll 1$), so that the law $\sigma_A = A^2\sigma_N$ holds only when $\alpha < \alpha_{\text{nuc}} = \sqrt{6}/(R_0A^{2/3}M_N) = \alpha_0/A^{1/3}$. For $\alpha > \alpha_{\text{nuc}}$, the nuclear cross section is $\sigma^{f,P}_A = A^{4/3}\sigma^{f,P}_{N_0}$, where $\sigma^{f,P}_{N_0} = (\alpha_0/\alpha)^2\sigma^{f,P}_N$ for the contributions of the f meson and the Pomeron. In the case of ω-meson exchange, $\sigma^\omega_N \sim \alpha^4$, so that there is an additional suppression $\sigma^\omega_A = A^{2/3}\sigma^\omega_{N_0}$, where $\sigma^\omega_{N_0} = (\alpha_0/\alpha)^4\sigma^\omega_N$. Moreover, in nuclei with large A the produced mesons can be absorbed. In the case of π^0-meson production, taking the mean free path of a π^0 meson in the nucleus to be $\lambda_{\pi^0} = 1/n_{\rm nuc}\sigma^{\rm abs}_{\pi^0 N} \approx 3.6\times10^{-13}$ cm,[4)] we find that $\lambda_{\pi^0} < R_{\rm nuc}$ for $A \gtrsim 27$. As we noted above, the state η_s is produced in the case of neutrino-induced η and η' production. Estimating the mean free path by using the cross section for interaction of the state η_s with the nucleon (see Sec. 2B), we find that $l_{\eta_s} < R_{\rm nuc}$ for $A > 370$. If η_s is successfully converted into $\eta(\eta')$ without leaving the nucleus, the opacity of the nucleus is determined by the interaction of all the components ($u\bar{u}, d\bar{d}, s\bar{s}$) of the η and η' wave functions with the nucleon. Estimating the cross sections $\sigma^{\rm abs}_{\eta N}$ and $\sigma^{\rm abs}_{\eta' N}$ according to the quark model, we obtain $\sigma^{\rm abs}_{\eta N} \simeq 12$ mb and $\sigma^{\rm abs}_{\eta' N} = 16$ mb, from which it can be seen that λ_η ($\lambda_{\eta'}$) is equal to $R_{\rm nuc}$ for $A \simeq 125$ ($A \simeq 53$).

Recent measurements[20] of the cross sections for charge-exchange conversion of π^- mesons into π^0 and η mesons on carbon nuclei indicate that the cross sections for absorption of η and π^0 mesons on the nucleon are equal with 5% accuracy. This result can be interpreted as an indication that the state $(u\bar{u} + d\bar{d})/\sqrt{2}$ formed in the interaction of a π^- meson with a nucleon can almost never be converted into an η meson in the carbon nucleus.

6. CONCLUSIONS

Our estimates show that the contribution to the processes (1) from the neutral vector current is small, and these processes are determined by the weak axial current. An investigation of such reactions will make it possible to obtain information about the transitions $f \to P^0\nu\bar{\nu}$ and $P \to P^0\nu\bar{\nu}$ and about the structure of the periphery of the nucleon in addition to the information[6] which can be provided by study of the process $\nu N \to \mu\pi N$ in the charged currents. The reactions (1) with production of η and η' mesons are of special interest. In the framework of the Weinberg–Salam model, the contribution to these processes from the isoscalar axial current is provided only by the neutral current of the strange quarks, so that the cross sections for the reaction (1) with η and η' production are determined by the admixture of strange quarks in the f meson and in the Pomeron. Our estimates show that these cross sections are very sensitive to the presence of the isoscalar axial current of the u and d quarks, and this fact can provide an additional possibility of verifying the existence of this current. In accordance with the qualitative picture proposed in Ref. 6, which considers the virtual mesons and Reggeons as quark correlations at the periphery of the nucleon, the process (1) with η and η' production is an indicator of the presence of strange quarks at the periphery of the nucleon. The inclusion of the effects of mesons with higher spin in Ref. 19 for the example of the $h(4^+)$ meson shows that the phenomenological description of the processes of development of such correlations at the periphery of the nucleon is self-consistent.

The studied total cross section for neutrino-induced production of pseudoscalar mesons in the Coulomb field of a nucleus (Fig. 2) is much smaller than the cross section for the process (1) due to scattering of the neutrino by virtual mesons; however, for very small momentum transfers to the nucleon, $k^2 \sim k^2_{\rm min}$, the process shown in Fig. 2 can be dominant in the differential cross section (see Sec. 3), and therefore its experimental separation requires detection and quite accurate determination of the momentum of the recoil nucleon. Study of the process of Fig. 2 will make it possible to obtain unique information about the practically unobservable processes $P^0 \to \nu\bar{\nu}\gamma$.[5)]

The decays $\eta \to \nu\bar{\nu}\gamma$ and $\eta' \to \nu\bar{\nu}\gamma$ are of special interest; the amplitude for the first of these is very sensitive to the degree of violation of $SU_f(3)$ symmetry, and the amplitude for the decay $\eta' \to \nu\bar{\nu}\gamma$ is in principle sensitive to the charges of the colored quarks (see Ref. 19).

The kinematic analysis carried out in the present paper is completely applicable for the treatment of exclusive processes of the type (1) (both in the neutral and in the charged currents) with production of heavy mesons, whose composition includes c, b, and other possible heavy quarks.

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[1)]Moreover, in the present paper we shall give special consideration to the contribution of mesons with higher spins. For the specific example of the 4^+ h meson it will be shown (see Sec. 4) that inclusion of the contribution of such mesons does not fundamentally alter the conclusions of Ref. 6.

[2)]The contribution of the A_1 meson is suppressed. The PCAC relation gives a connection between the amplitude for the transition $A^0_1 \to \eta$ and the $A_1 \to \eta\pi$ decay constant, which is equal to 0 by virtue of the Bose-Einstein principle, generalized to the case of SU(3) symmetry.

[3)]In the estimate of the cross sections due to the axial current in the meson region, we have taken the parameter value $s_M = 10$ GeV^2, at which the contributions of the mesons lying on a single Regge trajectory are equal (see Sec. 4). This value is lower than that used in Refs. 6 and 11 and in the estimate of the cross sections due to the vector current.

[4)]In the estimate of the mean free path, we have taken the absorption cross section $\sigma^{\rm abs}_{\pi^0 N} = m_\pi^{-2} \simeq 20$ mb and the value $R_0 = 1.2\times10^{-13}$ cm.

[5)]For a discussion of the difficulties in extracting information about such processes from the reactions $e^+e^- \to \pi^0(\eta)\gamma$, see Ref. 21.

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