Production of single photons in the exclusive neutrino process $\nu N \to \nu\gamma N$

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It is shown that the experimentally observed production of single photons in neutrino interactions involving neutral currents without visible accompaniment of other particles can be explained by the scattering of the neutrino by a virtual ω meson with small momentum transfer to a nucleon and subsequent coherent enhancement of the process in the nucleus.

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1. INTRODUCTION

In neutrino experiments performed at CERN using the chamber Gargamelle, more than ten events were detected in which it was observed that single photons with energy 1–10 GeV were produced without visible tracks of any other particles.[1] It can be assumed that the observed events correspond to the weak-electromagnetic process of single-photon production in the reaction

$$\nu N \to \nu\gamma N, \tag{1}$$

which is induced by neutral currents and is accompanied by small momentum transfer to the recoil nucleon (so that the latter leaves no tracks in the bubble chamber).[1)]

The investigation of the reaction (1) is of definite interest for the study of two-current processes. In principle, it makes it possible to extract both the P-even and P-odd amplitudes $\langle N | T(J_{EM}(x), J_W(0)|N\rangle$ off the mass shell, which determine the strength of the P-odd nuclear forces and the electromagnetic mass differences. Measurement of these amplitudes also makes it possible to carry out a direct test of dispersion relations.

V. D. Khovanskiĭ noted that the description of the reaction (1) in the vector-dominance model[2] (see Fig. 1) gives a value of order 10^{-41} cm^2 (under the assumption of a purely imaginary amplitude). This value is insufficient to explain the number of observed events (particularly in the region of production of comparatively soft photons, whose production cross section is of order 10^{-40} cm^2).

In the present paper, we estimate the cross section for the reaction (1) on the basis of the mechanism of photon production in the reaction of scattering of neutrinos by virtual mesons (M) (see Fig. 2). Such a mechanism was used previously by the present authors[3] to explain the production of fast single pions in neutrino interactions with charged currents. The matrix element corresponding to the diagram of Fig. 2 has the form

$$T = \frac{G}{\sqrt{2}} l_\mu H_{\mu\nu} A_\nu, \tag{2}$$

where $l_\mu = \bar{u}_2 \gamma_\mu (1+\gamma_5) u_1$ is the lepton current, A_ν is the polarization vector of the photon, and the tensor $H_{\mu\nu}$ is represented in the form of a sum of terms corresponding to scattering of the neutrino by various virtual mesons (M):

$$H_{\mu\nu} = \sum_M T^{(M)} P^{(M)} J_{\mu\nu}^{(M)}, \tag{3}$$

in which $T^{(M)}$ is the vertex for emission of a virtual meson (M) by the target nucleon, $P^{(M)}$ is the meson propagator, and $J_{\mu\nu}^{(M)} = \int \langle 0 | T(J_\mu^W(x), J_\nu^{EM}(y)) | M\rangle e^{iqx+ipy} d^4x d^4y$ is the weak-electromagnetic $Z^0 M\gamma$ vertex. The notation for the particle momenta is given in Fig. 2.

In accordance with the estimates of Ref. 3, we shall take into account the contributions to the diagram of Fig. 2 from only the π^0, ω^0, ρ^0, and f^0 mesons. According to the C-parity selection rules, the transitions $\pi^0 \to \gamma$ and $f^0 \to \gamma$ are due to the weak vector current, while the transitions $\omega^0 \to \gamma$ and $\rho^0 \to \gamma$ are due to the axial current. As will be shown below, the main contribution to the process (1) comes from the axial current as the result of scattering by the ω meson.

2. CROSS SECTION FOR THE REACTION ON VIRTUAL MESONS

The differential cross section for the process (1), expressed in terms of the invariants $s=(k_1+p_1)^2$, $s_1=(q+p_1)^2$, $s_2=(k_2+p)^2$, $t_1=k^2$, and $t_2=q^2$, has the form

$$\frac{d^4\sigma}{dt_1\, dt_2\, ds_2\, d\varphi} = \frac{\overline{|T|^2}}{(2\pi)^4 32 (s-M_N^2)^2 (s_2-t_1)}, \tag{4}$$

where φ is the Treiman–Yang aximuthal angle, M_N is the nucleon mass, and T is a sum of the contributions of the individual mesons:

$$T = T_{\pi^0} + T_{f^0} + T_{\omega^0} + T_{\rho^0} = \frac{G}{\sqrt{2}} l_\mu (H_{\mu\nu}^\pi + H_{\mu\nu}^f + H_{\mu\nu}^\omega + H_{\mu\nu}^\rho) A_\nu.$$

We note that in scattering by an unpolarized nucleon the pion amplitude does not interfere with the other amplitudes. We first estimate the contribution of the pion pole. The tensor $H_{\mu\nu}^\pi$ corresponding to pion exchange has the form

$$H_{\mu\nu}^\pi = \frac{g_{\pi N} (\bar{u}_2 \gamma_5 u_1)}{t_1 - m_\pi^2} f_{\pi\gamma}(k^2, q^2)\, \varepsilon_{\mu\nu\lambda\rho} q_\lambda p_\rho, \tag{5}$$

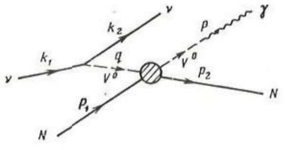

FIG. 1.

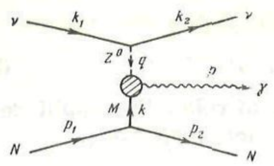

FIG. 2.

where $g_{\pi N}$ is the πN coupling constant ($g^2_{\pi N}/4\pi \simeq 15$) and $f_{\pi\gamma}(k^2, q^2)$ is the form factor of the weak-electromagnetic transition $\pi^0 \to \gamma$. We shall assume that the latter varies weakly off the mass shell of the pion: $f_{\pi\gamma}(k^2, q^2) \simeq f_{\pi\gamma}(M^2_M, q^2) \approx f_{\pi\gamma}(0, q^2)$. With the CVC hypothesis, the value of $f_{\pi\gamma}(0)$ can be related to the $\pi^0 \to 2\gamma$ decay constant:

$$f^2_{\pi\gamma}(0) = \frac{64(^1/_4 - \sin^2\theta_W)^2\,\Gamma_{\pi^0\to2\gamma}}{\alpha m^3_\pi}. \tag{6}$$

Since $\sin^2\theta_W$ is close to $\frac{1}{4}$, the vector $Z^0\pi\gamma$ vertex is strongly suppressed in the Weinberg-Salam model. In the integration over the phase space, we must take into account the fact that for small momentum transfers to the nucleon (we shall assume that $|t_1|_{\max} = x^2_m M^2_N$ and $x_m \ll 1$) $(s_2)_{\max} = (s/M_N)\sqrt{|t_1|}$, while s_1 is practically independent of the angle φ: $s_1 \simeq t_2 + M^2_N - st_2/s_2$. The invariants s_1, s_2, and t_2 are very simply related to the usual variables x and y of deep inelastic scattering[3]:

$$x \approx s_2/s;\quad y \approx -t_2/s_2 \approx s_1/s. \tag{7}$$

We must also take into account the fact that for large invariant masses s_1 of the γN system the virtual mesons in the diagram of Fig. 2 must be "Reggeized". Thus, in the region $s_1 < s_M$ we are dealing with scattering by a virtual meson, and in the region $s_1 > s_R$ with scattering by the corresponding Reggeon (s_M and s_R are the parameters which determine the transition to the Regge asymptotic behavior). In our estimates, we shall assume that $s_M \sim s_R \sim 15$–20 GeV^2 (Refs. 3 and 4) [the contribution from the Regge region to the cross section for the reaction (1) will be considered in the next section].

In the plane of the variables (x, y), scattering by a virtual meson corresponds to a band $0 \leqslant x \leqslant x_m$ and $0 \leqslant y \leqslant y_m = s_M/s$, and scattering by a Reggeon corresponds to a band $0 \leqslant x \leqslant x_m$ and $s_R/s = y_R \leqslant y \leqslant 1$. Assuming that the form factor $f_{\pi\gamma}(q^2)$ has a q^2 dependence of the form

$$f_{\pi\gamma}(q^2) = \frac{f_{\pi\gamma}(0)}{1 - q^2/\Lambda^2}, \tag{8}$$

with $\Lambda^2 \simeq 1$ GeV^2, we obtain the following expression for the total cross section of the reaction (1) on a virtual pion in the limit $\gamma = x_m s_M/\Lambda^2 \gg 1$:

$$\sigma^\pi_{tot} = \frac{G^2 g^2_{\pi N}(^1/_4 - \sin^2\theta_W)^2\,\Gamma_{\pi^0\to2\gamma}}{(2\pi)^3\,\alpha m^3_\pi} 4x^2_m\Lambda^4\Phi(a^2, \gamma), \tag{9}$$

where $a^2 = m^2_\pi/x^2_m M^2_N$ and the function $\Phi(a^2, \gamma)$ has the form

$$\Phi(a^2, \gamma) = \frac{1}{2}\left[\frac{1+2a^2}{1+a^2} - 2a^2\ln\frac{1+a^2}{a^2}\right]\left[\ln(1+\gamma) - \frac{3}{2}\right] - \frac{1}{4}\left(1 + a^2\ln\frac{1+a^2}{a^2}\right) + \frac{1}{2}F\left(\frac{1}{a^2}\right), \tag{9a}$$

in which

$$F(\xi) = \int_0^\xi \frac{\ln(1+z)}{z}\,dz$$

is the Spence function.

For $x_m = \frac{1}{4}$ and $s_M = 15$ GeV^2, we have $\sigma^\pi_{tot} \simeq 2\times10^{-43} \times (\frac{1}{4} - \sin^2\theta_W)^2$ cm^2. The contribution to $H_{\mu\nu}$ from the tensor f^0 meson has the form

$$H^f_{\mu\nu} = \frac{g_{fN}(\bar{u}_2\gamma_\sigma u_1)(p_1+p_2)_\lambda}{t_1 - m^2_f} P^{\mu\nu}_{\lambda\sigma} f_{f\gamma}(q^2), \tag{10}$$

where g_{fN} is the fN coupling constant [$g^2_{fN}/4\pi \simeq 27/8M^2_N$ (Ref. 3)] and $P^{\mu\nu}_{\lambda\sigma}$ is the polarization operator of the f meson. According to the CVC hypothesis, the value of the form factor $f_{f\gamma}(q^2)$ of the weak-electromagnetic transition $f \to \gamma Z^0$ at $q^2 = 0$ is related to the width $\Gamma_{f\to2\gamma}$ by the equation

$$f^2_{f\gamma}(0) = \frac{8m_f\Gamma_{f\to2\gamma}}{\alpha}(1 - 2\sin^2\theta_W)^2. \tag{11}$$

A measurement of the $f \to 2\gamma$ decay probability[5] gives $\Gamma_{f\to2\gamma} \approx 2.3$ keV. The double differential cross section $d^2\sigma_f/dxdy$ has the form

$$\frac{d^2\sigma_f}{dx\,dy} = \frac{G^2M^4_N(x^2_m - x^2)s}{(2\pi)^3}\left(\frac{g_{fN}}{m^2_f}\right)^2 f^2_{f\gamma}(q^2)\left(1 - \frac{x}{2}\right)^2(1-y). \tag{12}$$

Assuming that the form factor $f_{f\gamma}(q^2)$ has a q^2 dependence of the form (8), we obtain the following expression for the total cross section in the limit $\gamma \gg 1$:

$$\sigma^f_{tot} = \frac{G^2M^4_N}{(2\pi)^3}\left(\frac{g_{fN}}{m^2_f}\right)^2 \frac{8m_f\Gamma_{f\to2\gamma}(1-2\sin^2\theta_W)^2}{\alpha} x^2_m\Lambda^2\ln(1+\gamma), \tag{13}$$

from which, with $x_m = \frac{1}{4}$, $\Lambda^2 \simeq 1$ GeV^2, and $s_M \simeq 15$ GeV^2, we have $\sigma^f_{tot} \simeq 6\times10^{-43}$ cm^2. Let us now estimate the effects of the axial weak current in the reaction (1). The tensor $H^{(\omega,\rho)}_{\mu\nu}$ can be represented in the form

$$H^{(\omega,\rho)}_{\mu\nu} = \frac{g_{(\omega,\rho)N}}{t_1 - m^2_{(\omega,\rho)}}(\bar{u}_2\gamma_\lambda u_1) f_{(\omega,\rho)\gamma}(q^2)\,\varepsilon_{\mu\nu\lambda\rho}p_\rho. \tag{14}$$

We note that the vertices for the interaction of the ω and ρ with the nucleon can be decomposed into non-spin-flip and spin-flip parts:

$$\bar{u}_2\gamma_\lambda u_1 = (p_1+p_2)_\lambda + \frac{\bar{u}_2\sigma_{\lambda\rho}k_\rho u_1}{2M_N}, \tag{15}$$

from which we see that $\bar{u}_2\gamma_\lambda u_1 \approx (p_1+p_2)_\lambda$ for small $|\mathbf{k}|$; therefore we shall neglect the spin-flip part of the amplitude in the calculations.

It follows from the PCAC hypothesis that

$$f_{(\omega,\rho)\gamma}(0) = \frac{f_\pi g_{(\omega,\rho)\pi\gamma}}{\sqrt{2}}. \tag{16}$$

The constant $g_{\omega\pi\gamma}$ of the decay $\omega \to \pi\gamma$ is related to the width of this decay by the equation

$$\Gamma_{\omega\to\pi\gamma} = g^2_{\omega\pi\gamma}m^3_\omega/96\pi.$$

This relation also holds for the ρ meson. The contribution of the ρ-meson pole is suppressed in comparison with the corresponding ω contribution by almost two orders of magnetude because $g_{\rho N} \approx \frac{1}{3}g_{\omega N}$ and $g_{\rho\pi\gamma} \simeq \frac{1}{3}g_{\omega\pi\gamma}$. We shall therefore consider only the contribution of the ω pole. The corresponding differential cross section is

$$\frac{d^2\sigma_\omega}{dx\,dy} = \frac{G^2M^2_N(x^2_m - x^2)}{(2\pi)^3 8}\left[\frac{g_{\omega N}f_{\omega\gamma}(0)}{m^2_\omega}\right]^2 \frac{s^2xy(2-2y+y)}{(1+sxy/\Lambda^2)^2}. \tag{18}$$

In the asymptotic regime with $\gamma \gg 1$, the total cross section has the form

$$\sigma_{tot}^{\omega} \simeq \frac{G^2 M_N}{(2\pi)^3 4}\left[\frac{g_{\omega N} f_{\omega\gamma}(0)}{m_\omega^2}\right]^2 x_m \Lambda^4 [F(\gamma) - \ln(1+\gamma)], \quad (19)$$

where $F(\gamma)$ is the Spence function, and its value is $\sigma_{tot}^{\omega} \simeq 1.5\times 10^{-41}$ cm^2 (for $x_m = \frac{1}{4}$, $s_M \simeq 15$ GeV^2 and $\Lambda^2 \simeq 1$ GeV^2). This value of the total cross section is sensitive to variation of the parameter s_M. For example, when s_M varies from 15 to 10 GeV^2 the cross section σ_{tot}^{ω} is reduced by a factor 2. Thus, the contribution of the axial current to the reaction (1) due to scattering by the ω meson is much greater than the contribution of the vector current (scattering by π^0 and f^0 mesons). As a result, the contribution of the interference terms involving the f^0 meson is suppressed.

3. CROSS SECTION OF THE REACTION (1) IN THE REGGE REGION

A. Estimate of the contribution of the weak vector current

The CVC relation makes it possible to express the amplitude for the reaction (1) in the Regge region[2)] in terms of the amplitude for $VN \to VN$ scattering of vector mesons V by the nucleon[2] (see Fig. 1). The amplitude for $VN \to VN$ scattering in the high-energy limit, when it is determined by only Pomeron exchange, has the form

$$T = V_{\mu 1} V_{\nu 2} e_{\mu\nu\lambda\rho} (\bar{u}_2 \gamma_\lambda u_1) p_\rho \mathrm{Im}\, K^{VN}, \quad (20)$$

where $p = (k_1 + k_2)/2$, k_1 and k_2 ($V_{\mu 1}$ and $V_{\nu 2}$) are the momenta (wave functions) of the vector mesons, and $\sigma_{tot}^{VN} = \mathrm{Im} K^{VN}$. According to the CVC relation, the constants of the $\nu\nu V$ transition have the form[2]

$$f_{\nu\nu V} = \frac{G}{\sqrt{2}} \frac{\xi_V}{g_V}.$$

Since $g_\rho \ll g_\omega, g_\varphi$, we have $f_{\nu\nu\rho} \gg f_{\nu\nu\omega}, f_{\nu\nu\varphi}$, and the amplitude for the reaction (1) is determined mainly by the amplitude for $\rho N \to \rho N$ scattering. The differential cross section for the reaction (1) due to the vector-current contribution in the Regge region has the form

$$\frac{d^2\sigma^V}{dx\,dy} = \frac{G^2 M_N^2 (x_m^2 - x^2)}{(2\pi)^3 8}\left[\frac{e\xi_\rho \sigma_{tot}^{\rho N}}{g_\rho^2}\right]^2 \frac{s^2 xy(2-2y+y^2)}{(1+(sxy/\Lambda^2))^2}, \quad (21)$$

where $\xi_\rho = 1 - 2\sin^2\theta_W$ and $g_\rho^2/ \simeq 2.56$.

The x and y dependence in the expression (21) is the same as the corresponding dependence in Eq. (18) in the meson region. For $x_m = \frac{1}{4}$, $\Lambda^2 \simeq 1$ GeV^2, and $s_R \simeq 15$ GeV^2, we obtain from Eq. (21) the estimate $\sigma^V \approx 2\times 10^{-43} \times \ln(x_m s/\Lambda^2)$ cm^2 for the total cross section. The small value of σ^V in comparison with the estimates of Ref. 2 is due to the fact that we have considered only the region of small momentum transfers $|\mathbf{k}| < 250$ MeV/c.

B. Estimate of the contribution of the weak axial current

The contribution of the axial current is determined by the Reggeized amplitude (14), which has the form

$$H_\mu^{\omega} = \Phi_R^{\omega}(t_1, t_2, s_2) \varepsilon_{\mu\nu\lambda\rho} A_\nu (\bar{u}_2 \gamma_\lambda u_1) p_\rho, \quad (22)$$

where

$$\Phi_R^{\omega}(t_1, t_2, s_2) = (\Phi_R^{\omega})_0 (t_1, t_2, s_2) \eta_\omega (s_1/s_0)^{\alpha_\omega(0)-1}. \quad (23)$$

The PCAC relations enable us to relate the amplitude (23) to the amplitude for the reaction $\pi N \to \rho N$:

$$(\Phi_R^{\omega})_0 = \frac{f_\pi e}{\sqrt{2}\, g_\rho} (\Phi_{\pi\rho})_0, \quad (24)$$

where

$$\frac{(\Phi_{\pi\rho}^{\omega})_0^2}{16\pi} \simeq \frac{10^4}{256} \frac{\mathrm{mb}}{(\mathrm{GeV}/c)^4} \quad \text{(see Refs. 3 and 6).}$$

From Eqs. (22)–(24) we obtain the following expression for the differential cross section in the Regge region:

$$\frac{d^2\sigma_R^{\omega}}{dx\,dy} = \frac{G^2 M_N^2 (x_m^2 - x^2)}{(2\pi)^3 8}\left(\frac{f_\pi e}{\sqrt{2}\, g_\rho}\right)^2 \left|\left(\Phi_{\pi\rho}^{\omega}\right)_0\right|^2 \frac{2 s_0 s x (2-2y+y^2)}{(1+sxy/\Lambda^2)^2}. \quad (25)$$

The axial-current contribution σ^A to the total cross section for the reaction (1) in the Regge region ($s_1 > s_R$) has the form

$$\sigma^A = \frac{G^2 M_N}{(2\pi)^3 8}\left(\frac{f_\pi e}{\sqrt{2} g_\rho}\right)^2 |(\Phi_{\pi\rho}^{\omega})_0|^2 \frac{4 s_0}{s_R}\left(1 - \frac{s_R}{s}\right) x_m^2 \Lambda^4 \ln\left(1 + \frac{x_m s_R}{\Lambda^2}\right). \quad (26)$$

For $s \gg s_R \simeq 15$ GeV^2, we have $\sigma^A \simeq 10^{-42}$ cm^2. Comparison of our estimates of σ^V and σ^A with the estimates of the preceding section shows that the cross section for the reaction (1) is the Regge region ($s_1 > s_R$) is small and that the main contribution to the total cross section for the reaction (1) comes from scattering of the neutrino by a virtual ω meson:

$$\sigma_{tot} \sim \sigma_\omega^M \sim 10^{-41}\ \mathrm{cm}^2.$$

This value of the total cross section for the reaction (1) on a free nucleon is insufficient to account for the total number of events in the experiments of Ref. 1. However, in the case of scattering of neutrinos by nuclei with small momentum transfer to the nucleon in processes involving production of single photons, there is a coherent enhancement, which will be considered in in the next section.

4. COHERENT PRODUCTION OF PHOTONS ON NUCLEI

The region of momentum transfers to the nucleon which we have considered corresponds to the characteristic momenta of the nucleons in nuclei. Since the isotopic spin of the ω meson is 0 and the cross section for the reaction (1) is determined by the non-spin-flip amplitude of ω-meson exchange, as follows from (15), all the nucleons of the nucleus give a coherent contribution to the reaction (1) on a nucleus. The calculations of the preceding section can be applied directly to the estimation of the coherent production of photons on nuclei. It is obvious that the coherent cross section for photon production on nuclei with no change in the state of the nucleus is

$$\sigma_{tot} \approx A^2 \sigma_{tot}^{\omega}, \quad (27)$$

where σ_{tot}^{ω} is taken from Eq. (19). For the conditions of the experiment of Ref. 1 in a propane–freon chamber (90.5% propane C_3H_8 and 9.5% freon CF_3Br), the total cross section for production of single photons, calculated per nucleon according to (27), is $\sigma_N \simeq 20\sigma^{\omega}_{\rm tot}$, which seems to be sufficient to account for the total number of neutrino events involving single photons.

A characteristic feature of the mechanism under consideration is the rather broad angular distribution of single photons with respect to the direction of the incident neutrino (particularly for soft photons). The angular and energy distribution of the photons obtained from (18) has the form

$$\frac{d^2\sigma}{dE_\gamma d\cos\theta_{\nu\gamma}} = \frac{G^2 M_N^2}{(2\pi)^3 8}\left[\frac{g_{\omega N} f_{\omega\gamma}(0)}{m_\omega^2}\right]^2 \frac{1}{[1-(q^2/\Lambda^2)]^2} \times \frac{4E_\nu^2 E_\gamma^3(1-\cos\theta_{\nu\gamma})}{E_{\nu'}^2}\left(x_m^2 - \frac{4E_\nu^2 E_\gamma^2}{E_{\nu'}^2 M_N^2}\sin^4\frac{\theta_{\nu\gamma}}{2}\right). \qquad (28)$$

Here E_ν is the energy of the incident neutrino, and $E_{\nu'}$ is the energy of the scattered neutrino. (Clearly, for small momentum transfers to the nucleon this expression is also valid for the coherent production of photons on nuclei.) It follows from (28) that the limiting production angles of the photons are determined by the value $\theta_{\max} = (2|\mathbf{k}|E_{\nu'}/E_\nu E_\gamma)^{1/2}$, where $|\mathbf{k}| = x_m M_N$ is the momentum of the recoil nucleon. Since the cross section (28) vanishes at $\theta_{\nu\gamma}=0$, the most probable emission angle of a single photon is

$$\theta_0 = \sqrt{\frac{12}{7}}\sqrt{\frac{|\mathbf{k}|E_{\nu'}}{E_\nu E_\gamma}}.$$

At $E_\nu = 25$ GeV and $E_\gamma = 10$ GeV, we have $\theta_{\max} \simeq 0.17$ and $\theta_0 \simeq 0.8\,\theta_{\max} \simeq 0.14$. This angular dependence of the production of single photons is qualitatively consistent with the observed data.[1] Thus, for $E_\gamma \simeq 10$ GeV five events have been observed in the angular interval 40–130 mrad, whereas for $20 < E_\gamma \leqslant 40$ GeV three events have been observed in the angular interval $20 < \theta_{\nu\gamma} < 30$ mrad.[3)]

Our estimates show that the contribution of t-channel exchange of the ω meson is dominant in the amplitude for the reaction (1). This corresponds to an enhancement of the real part of the amplitude for the reaction (1) in comparison with the value obtained from dispersion relations. The contribution of ω exchange is due to the axial current, so that the P-odd two-current nucleon amplitude is enhanced. It is possible that this enhancement of the real part of the two-current amplitudes produces an enhancement of the P-odd nuclear forces or, for example, of the P-odd effects in the reaction $np \to d\gamma$. This enhancement may be associated with the appearance of additional terms in the dispersion relations besides the s-channel pole terms. Therefore the study of the reaction (1) makes it possible to carry out a direct test of the dispersion relations.

Our estimates of the total cross sections are very sensitive to the values of s_M and s_R, which determine the transition to the Regge asymptotic regime. Thus, if s_M is varied from 15 to 10 GeV^2, the value of σ^ω is reduced by a factor 2 (Sec. 2). At the same time, a decrease of s_R increases the contribution of the Regge region to the total cross section [see (26)]. An analysis of the differential cross sections (18), (21), and (25) shows that the maximum of the differential cross section $d^2\sigma(E_\gamma)/dE_\gamma d\theta_{\nu\gamma}$ lies precisely in the energy interval E_γ from $\sim(s_M/2M_N)$ to $(s_R/2M_N)$ corresponding to the region of transition to the Regge description. A similar distribution can also be expected[3] in exclusive neutrino processes involving production of single pions at the periphery of a nucleon. Although the statistics of single photons in the experiment of Ref. 1 are too poor to draw definite conclusions, the data presented in Fig. 4 of Ref. 1 (if we consider only the region $E_\gamma > 3$ GeV) indicate an increase of dN_γ/dE_γ at energy $E_\gamma \sim 10$ GeV and an abrupt decrease at higher energies. The maximum in the distribution of dN_γ/dE_γ at $E_\gamma = 10$ GeV corresponds to $s_M \simeq 20$ GeV^2. We note that it was precisely this value that was used in Ref. 4 as the upper limit of applicability of the concepts of scattering by virtual mesons. In Ref. 3 a space-time picture was proposed for the development of quark correlations in the confinement region. According to these ideas,[3] the value of s_M characterizes the time $\tau_M = 2M_N/s_M$ of formation of a virtual meson at the periphery of a nucleon, which is determined by quark interaction processes at large distances. Thus, the study of the reaction (1) makes it possible to obtain additional information about the physics of the processes in the confinement region. Since according to the proposed mechanism the production of single photons takes place coherently on nuclei, experiments in chambers filled with different substances may serve as a test of this mechanism of the reaction (1).

In conclusion, we thank P. A. Gorichev, K. A. Ter-Martirosyan, A. N. Shelkovenko, and especially V. D. Khovanskiĭ for stimulating and valuable discussions.

[1)]This may correspond to momentum transfers less than 250 MeV/c, i.e., energies of the recoil nucleons less than 30 MeV.

[2)]According to Ref. 3, this relation may break down in the region of meson exchanges in the reaction (1), owing to the fact that the transition to the Regge description in lepton–hadron processes may occur at higher energies than in hadronic reactions.

[3)]We note that, in addition to the high-energy photons, a rather large number of "soft" photons with energy $E_\gamma \sim 1$ GeV is observed experimentally. The production mechanism of such "soft" photons might be the production of the Δ isobar by the neutral current on the nucleons of the nucleus, $\nu N \to \nu\Delta$, followed by radiative decay of the isobar, $\Delta \to N\gamma$. Owing to the suppression of large momentum transfers by the form factor of the transition $N \to \Delta$, most of the isobars are produced with energy less than 1 GeV. Therefore a rough estimate of the cross section for this process can be obtained in the form $\sigma \simeq \alpha\sigma_{\nu N\to\nu\Delta} \sim 10^{-40}$ cm^2 (where the factor $\alpha = 1/137$ determines in order of magnitude the fraction of radiative decays of the isobar).

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