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ЛАБОРАТОРИЯ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ

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VECTOR DOMINANCE MODEL AND SUM RULES FOR THE HIGH-ENERGY PHOTON-NUCLEON INTERACTION

Submitted to XIV International Conference on High Energy (Vienna)

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Герасимов С.Б. Е2-3926

Модель векторной доминантности и правила сумм для взаимодействия фотонов с нуклонами при высоких энергиях

В рамках модели векторной доминантности обсуждаются правила сумм для сечений фоторождения векторных мезонов и для полных сечений фотопоглощения на нуклонах.

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Vector Dominance Model and Sum Rules for the High-Energy Photon-Nucleon Interaction

Within the vector dominance model the sum rules for the cross sections of vector-meson photoproduction and for the total cross sections of photon and meson interactions with nucleons are being discussed.

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The test of vector dominance model (VDM) for the hadron electromagnetic interactions [1,2] is of great importance. The validity of VDM would result in many relations between the amplitudes of strong and electromagnetic processes and would also implicate the consequences of principal value in the current algebra theory, effective Lagrangians etc.[3]

In the present communication we are dealing with the two topics in the framework of VDM:

1. The ratio of the cross sections for high-energy neutral vector-meson photoproduction by nucleons.

2. The relation between the total cross sections of photon and meson interactions with nucleons. All these questions have been discussed in many papers (one can find the list of references, for example, in reviews[4], see also[5,6]). The results of the present work, which the author believes to be new, are summarized as follows:

1. The ϕ-meson photoproduction cross section is shown to be sensitive both to deviation of the $\omega-\phi$ mixing angle[10] from its "ideal" value $\theta \approx 35.3^{\circ}$ and to possible violation of the U-invariance

in hadron electromagnetic interactions[9]. The inclusion of these modifications into the calculation, results in a considerable suppression of the ϕ -photoproduction, thus reducing the disagreement between theory[4] and experiment[7].

2. The finite energy dispersion sum rules[12] are used to define the integral of the total γP -interaction cross section in terms of the photon-vector-meson transition constant and parameters, describing the high energy meson-nucleon scattering. The value of the constant obtained from the sum rule is compared with the data of various experiments[7,17-22]. According to VDM we can write the amplitudes for reactions $\gamma + B \to V_i + B$ and $\gamma + B \to \gamma + B$ as

$$< V_i B | \gamma B > = \sum_j G_{\gamma V_j} < V_i B | V_j B >, \tag{1}$$

$$< \gamma B | \gamma B > = \sum_{i,j} G_{\gamma V_i} G_{\gamma V_j} < V_i B | V_j B >,$$

with $V_{i,j} = \rho^0, \omega, \phi$ and $B = P, N$. The coupling constant $G_{\gamma V_i}$ is defined through the matrix element of transition

$$< 0 | j_\mu (0) | V_i (q) > = \frac{G_{\gamma V_i} m^2_{V_i}}{(2\pi)^{3/2} (2 q^0)^{1/2}} \epsilon_\mu (q) . \tag{2}$$

In eq.(2) j_μ is the electromagnetic current, $\epsilon_\mu (q)$ is the polarization 4-vector of meson with momentum q and mass m_{V_i}. The important thing to notice is that $G_{\gamma V_i} = G(q^2)$ may indeed be the function of q^2. To describe the amplitudes $< V_i B | V_j B>$ in a high energy region, the Regge-pole model or quark model are usually used[4-6].

We make use of the additive quark model [8]. In the quark model the meson state vectors are of the form

$$|\rho^0> = \frac{1}{\sqrt{2}} |\bar{p}p - \bar{n}n>,$$

$$|\omega> = \frac{\cos\delta}{\sqrt{2}} |\bar{p}p + \bar{n}n> - \sin\delta\, |\bar{\lambda}\lambda>, \tag{3}$$

$$-|\phi> = \cos\delta\, |\bar{\lambda}\lambda> + \frac{\sin\delta}{\sqrt{2}} |\bar{p}p + \bar{n}n>,$$

where p , n , λ are usual symbols for quarks, $\delta = \theta_V - \theta$, θ_V is the $\omega - \phi$ mixing angle whose "ideal" value is θ , $\mathrm{tg}\,\theta = 1/\sqrt{2}$. We shall assume further that the spin dependence of scattering amplitudes is unimportant in the region of high energies and small angles. It is possible then to express the $< V_i B | V_j B >$ in terms of the pseudoscalar meson amplitude scattering. Taking all this into account, we obtain

$$<\rho^0 B | \gamma B> = P\, G_{\gamma\rho} + 3A\,(G_{\gamma\omega} \cos\delta - G_{\gamma\phi} \sin\delta), \tag{4}$$

$$<\omega B | \gamma B> = P\,(G_{\gamma\omega} \cos 2\delta - G_{\gamma\phi} \sin 2\delta) + 3A\, G_{\gamma\rho} \cos\delta +$$

$$+ S\,(G_{\gamma\omega} \cos^2\delta + \frac{1}{2} G_{\gamma\phi} \sin 2\delta), \tag{5}$$

$$<\phi B | \gamma B> = -P\,(G_{\gamma\phi} \cos 2\delta + G_{\gamma\omega} \sin 2\delta) - 3A\, G_{\gamma\rho} \sin\delta +$$

$$+ S (G_{\gamma\phi} \cos^2 \delta + \frac{1}{2} G_{\gamma\omega} \sin 2\delta) , \tag{6}$$

$$<\gamma B \mid \gamma B> = P [G^2_{\gamma\rho} + (G^2_{\gamma\omega} - G^2_{\gamma\phi}) \cos 2\delta - 2 G_{\gamma\omega} G_{\gamma\phi} \sin 2\delta] +$$

$$+ 6 A G_{\gamma\rho} (G_{\gamma\omega} \cos \delta - G_{\gamma\phi} \sin \delta) + \tag{7}$$

$$+ S (G^2_{\gamma\phi} \cos^2 \delta + G^2_{\gamma\omega} \sin^2 \delta + G_{\gamma\omega} G_{\gamma\phi} \sin 2\delta) ,$$

where

$$P = 1/2 (< \pi^+ B \mid \pi^+ B > + < \pi^- B \mid \pi^- B >) , \tag{8}$$

$$A = 1/2 (< K^+ B \mid K^+ B > + < K^- B \mid K^- B > - < K^0 B \mid K^0 B > - < \bar{K}^0 B \mid \bar{K}^0 B >) , \tag{9}$$

$$S = 1/2 (< K^+ B \mid K^+ B > + < K^- B \mid K^- B > + < K^0 B \mid K^0 B > + < \bar{K}^0 B \mid \bar{K}^0 B >) . \tag{10}$$

Note, that in the Regge-pole model the energy dependence of P and S is dominated by the Pomeranchuk poles, while A includes the contributions from the Regge-trajectories with isospin exchange $I = 1$ in the t-channel from which the A_2 -trajectory is usually supposed to be dominant. From the quark structure of state-vectors of V_i's one can derive the following relation

$$G_{\gamma\rho} : G_{\gamma\omega} : G_{\gamma\phi} = 3 : (\cos\delta + \sqrt{2}\, x \sin\delta) : (\sqrt{2}\, x \cos\delta - \sin\delta) , \tag{11}$$

where we have accepted the "broken" symmetry ratio for the quark amplitudes

$$< \gamma \,|\, \bar{p}\, p > \,:\, < \gamma \,|\, \bar{n}\, n > \,:\, < \gamma \,|\, \bar{\lambda} \lambda > \, = 2 : -1 : -x \,. \tag{12}$$

When $x = 1$ we come to the well-known octet structure for electromagnetic current. The change of the electromagnetic interaction of "strange" quarks as a possible model of the U-symmetry breaking was proposed and discussed earlier, together with some experimental implications[9]. We shall estimate now the effect of inequalities $\delta \neq 0$ and $x \neq 1$ in the high energy vector meson photoproduction. Experimental cross sections are fitted at fixed energy in the following form[7]

$$\frac{d\sigma}{d\Delta^2} = a \exp(-b\,\Delta^2)\,, \tag{13}$$

where Δ^2 is the momentum transfer.

In Table 1 the ratios $r(V_i\, B) = a(V_i\, B)/a(\rho^0 B)$ obtained experimentally [7] and computed theoretically with the help of eqs.(4)-(12) for several sets of δ and x are given for $E_\gamma = 5$ GeV. The forward scattering amplitudes in eqs. (8)-(10) were supposed to be pure imaginary and calculated with the help of the optical theorem and experimental cross section. In our normalization $a(\rho^0 P)$ in eq.(13) is defined by

$$a(\rho^0 P) = \frac{1}{64\pi}\Big[G_{\gamma\rho}\big(\sigma(\pi^+ P) + \sigma(\pi^- P)\big) + \\ + 3\big(G_{\gamma\omega}\cos\delta - G_{\gamma\phi}\sin\delta\big)\big(\sigma(K^+ P) + \sigma(K^- P) - \sigma(K^+ N) - \sigma(K^- N)\big)\Big]^2\,, \tag{14}$$

where we have used $\sigma(K^0P) + \sigma(\bar{K}^0P) = \sigma(K^+N) + \sigma(K^-N)$ as a consequence of charge symmetry. The formulae for $a(\omega B)$ and $a(\phi B)$ can be easily obtained using eqs. (5) (6), (8)-(10). The value $\delta = 0.08$ in Table 1 corresponds to the $\omega - \phi$ mixing angle $\theta_V = 40^0$ which follows from the mass formula [10] and $x = 0.8$ was chosen in ref.[9] to bring the Λ -hyperon magnetic moment into agreement with experiment. Numerically, the x-value is close to the ratio $m_\rho / m_\phi = 0{,}75$, proposed in an other scheme of the symmetry breaking[11]. One can see that disagreement between theory and experiment in the ϕ-photoproduction is reduced to one standard deviation instead of nine, when $\delta = 0$ and $x = 1$. The relationship between the ρ^0 and ω-photoproduction depends weakly on the variation of δ and x. The chain of inequalities

$$r(\omega P) > \frac{G^2_{\gamma\omega}}{G^2_{\gamma\rho}} > r(\omega N) \tag{15}$$

is accounted for a relatively large value of $A(E)$ at $E = 5$ GeV whose signs are opposite for proton and neutron according to eq.(9). When the energy increases the $A(E)$ goes to zero (in the Regge-pole model we would have $A(E)/P(E) \underset{E \to \infty}{\to} E^{\alpha_{A_2}(0) - 1} = E^{-0{,}6}$) so that the ratio of the ρ^0 and ω-photoproduction by nucleons will approach

$$\sigma(\rho^0) : \sigma(\omega) = G^2_{\gamma\rho} : G^2_{\gamma\omega} = 9 : 1 \tag{16}$$

which should be valid in the intermediate energy region only for the coherent photoproduction by the isoscalar nuclei (D , ^{4}He, ^{16}O).

We shall turn now to the calculation of the absolute values of constants $G_{\gamma v_i}$ on the basis of dispersion sum rules. The starting point for derivation is the Cauchy formula

$$f(E) = \frac{1}{2\pi i} \oint \frac{f(E')}{E' - E} \, dE' \tag{17}$$

for the forward photon-nucleon scattering amplitude $f = f(E)$. The contour of integration in the complex energy plane in eq.(17) is defined by the general requirements of microcausality and spectrality. Omitting the standard technique[12], we shall write the sum rules in their final form[14]

$$-2\pi^2 \frac{\alpha}{M} = \int_0^R \sigma_{\gamma P}(E) \, dE + J_0(R), \tag{18}$$

$$0 = \int_0^R E^2 \sigma_{\gamma P}(E) \, dE + J_2(R), \tag{19}$$

where $\alpha = 1/137$, M is nucleon mass, $\sigma_{\gamma P}(E)$ is total γP -cross section and $J_n(R)$ are the integrals taken along the large circle C_R of radius R

$$J_n(R) = -i\pi \int_{C_R} E^{n-1} f(E) \, dE \, . \tag{20}$$

For large values of R the validity of eqs. (7)-(10) in the whole complex plane is assumed. The large circle integrals of the meson-baryon amplitudes were shown[12] to be approximated quite well by

$$J_n(R) = -\int_0^R E^n \left(\sum_i B_i \left(\frac{E}{E_0}\right)^{\alpha_i(0)-1} \right) dE \,, \tag{21}$$

where B_i and $\alpha_i(0)$ are the well-known Regge-pole model parameters.

In what follows we shall use

$$\sigma(\pi^+ P) + \sigma(\pi^- P) = 2(B_p + B_{p'} E^{-0,5}) \tag{22}$$

$$\sigma(K^+ P) + \sigma(K^- P) = 2(C_p + C_{p'} E^{-0,5} + C_{A_2} E^{-0,8}) \tag{23}$$

with[13] $B_p = 19{,}7$ mb, $B_{p'} = 19{,}6$ mb, $C_p = 17{,}7$ mb $C_{p'} = 5{,}7$ mb, $C_{A_2} = 1{,}38$ mb and all energies are taken in GeV. The expression for the sum $\sigma(K^0 P) + \sigma(\bar{K}^0 P)$ can be obtained from eq.(23) by changing the sign of C_{A_2}. The experimental values of $\sigma_{\gamma P}(E)$ in the energy interval $E \le R = 5$ GeV were found[14] from refs.[15,16]. Due to rather poor accuracy of the experimental data above 2 GeV, we give only the resulting calculation for the sum rule (18)

$$-0{,}06 \text{ mb GeV} = 0{,}59 \text{ mb GeV} - G^2_{\gamma\rho}\ 240 \text{ mb GeV} \tag{24}$$

from which it follows

$$G^2_{\gamma\rho} = 0{,}37\,\alpha \,. \tag{25}$$

The value of $J_0(R)$ in eq.(18) was found at $x = 1$ and $\delta = 0$. With variation of x and δ the final result (25) is changed negligibly in comparison with the range of experimental uncertainties, which are assumed to be about 15%. In Table II the values $G_{\gamma\rho} = G(m^2_\rho)$ are given, obtained from both the vector-meson lepton decays[17-20] and the inverse reaction $e^+ + e^- \to \rho^0 \to \pi^+ + \pi^-$ observed recently in the colliding e^+e^--beam experiments [21,22]. The constant $G_{\gamma\rho} = G(m_\rho^2)$ was found from

$$G^2_{\gamma\rho} = \frac{3B\Gamma(\rho^0 \to \pi^+\pi^-)}{\alpha m_\rho}, \tag{26}$$

where $B = \Gamma(\rho^0 \to \ell^+\ell^-)/\Gamma(\rho^0 \to \pi^+\pi^-)$, $m_\rho = 764$ MeV and the ρ^0-meson width was taken throughout to be $\Gamma_\rho = 130$ MeV for the exception of the last row in Table II where we make use of $\Gamma_\rho = 90$ MeV claimed by the Novosibirsk group [21].

In view of the possible dependence $G_{\gamma V} = G(q^2)$ it is of interest to compare our value (25) with other results for $G_{\gamma\rho}(0)$. Here we use the forward ρ^0-photoproduction by protons. The $a(\rho^0 P)$ value entering eq.(13) was measured at $E = 5$ GeV to be [7]

$$a_{exp}(\rho^0 P) = (0{,}129 \pm 0{,}012)\ \mathrm{mb}/\mathrm{GeV}^2. \tag{27}$$

The comparison of eq.(27) with theoretical value (14)

$$a(\rho^0 P) = G^2_{\gamma\rho}(0)\ 43{,}2\ \mathrm{mb}/\mathrm{GeV}^2 \tag{28}$$

gives

$$G^2_{\gamma\rho}(0) = (0{,}41 \pm 0{,}04)\ \alpha \tag{29}$$

which is in more favourable agreement with eq.(25) than with $G_{\gamma\rho}(m_\rho^2)$ listed in Table II. To get a more definite conclusion about the off-mass-shell effects in $G_{\gamma\rho}(q^2)$ much more accuracy is needed both in theoretical treatment and in experimental data on high-energy γP-interaction.

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Table 1

		$r(\omega P)$	$r(\phi P)$	$r(\omega N)$	$r(\phi N)$
$\delta = 0$	$x = 1$	0,18	0,031	0,056	0,035
$\delta = 0{,}08$	$x = 1$	0,2	0,02	0,062	0,029
$\delta = 0{,}08$	$x = 0{,}8$	0,19	0,011	0,062	0,017
Experiment [7]		$0{,}21 \pm 0{,}04$	$0{,}006 \pm 0{,}0025$	—	—
Experiment [23]		$0{,}22 \pm 0{,}06$	$0{,}012 \pm 0{,}006$	——	

Table II

Reaction	$B\,10^5$	$G^2_{\gamma\rho}(m^2_\rho)\,\alpha^{-1}$	Reference
$\pi^- + p \to e^+ + e^- + n$	$3{,}5 \pm 0{,}9$	0,34	17
$\gamma + C \to \mu^+ + \mu^- + C$	$5{,}9 \pm 1{,}5$	0,56	18
$\pi^- + C \to \mu^+ + \mu^- + \ldots$	$5{,}8 \pm 1{,}2$	0,55	19
$\gamma + C \to e^+ + e^- + C$	$6{,}5 \pm 1{,}4$	0,62	20
$e^+ + e^- \to \pi^+ + \pi^-$	$5{,}41 \pm 0{,}89$	0,52	22
$e^+ + e^- \to \pi^+ + \pi^-$	$4{,}8 \pm 0{,}7$	0,32	21