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ELECTRIC DIPOLE PHOTOABSORPTION AND QUARK STRUCTURE OF NUCLEONS

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ЭЛЕКТРИЧЕСКОЕ ДИПОЛЬНОЕ ФОТОПОГЛОЩЕНИЕ И КВАРКОВАЯ СТРУКТУРА НУКЛОНОВ

Рассмотрены правила сумм электрического дипольного фотопоглощения в модели составляющих кварков. Экспериментальные данные по электрическому дипольному фотопоглощению на протоне до энергии фотонов 1,2 ГэВ хорошо описываются в модели кварков правилами сумм нулевого и отрицательного первого моментов. Первое правило сумм предсказывает равенство вкладов в интегралы для фотополглощения на протоне и нейтроне, что делает важным получение качественных данных по фотопоглощению на нейтроне. Важную роль в описании играет учет примеси мультиплета $[70,0^+]$ в нуклоне, которая необходима с точки зрения массовых формул для барионов.

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ELECTRIC DIPOLE PHOTOABSORPTION AND QUARK STRUCTURE OF NUCLEONS

The sum rules for electric dipole photoabsorption are considered in the framework of constituent quark model. Experimental data on electric dipole photoabsorption on a proton up to the photon energy of 1.2 GeV are well described by sum rules of zero and first negative moments. The first sum rule predicts equality of contributions into integrals for photoabsorption on proton and neutron, this making important to obtain qualitative photoabsorption data on neutron. The second sum rule indicates that in nucleon there is large admixture of $[70,0^+]$ multiplet, the latter being necessary also from the viewpoint of mass formulae for baryons.

Yerevan Physics Institute
Yerevan 1985

1. Introduction.

The correlation between QCD and the constituent quark model (CQM) in the description of the soft processes remains vague so far (see, e.g. [1]).

Starting from quite different points (massless (current) quarks and, generally speaking, strong spin dependence in QCD; massive quarks and SU(6)-symmetry (absence of spin dependence) in CQM), both approaches lead to a striking agreement with each other (and with experiment) in the description of static and some dynamical (in the region of small q^2) properties of light hadrons, where nonperturbative effects are to be essential. Relativization of CQM still improves this agreement (see, e.g. [2]). From this point of view, of great importance is to understand the reasons of this agreement and finally the construction of CQM from (nonperturbative) QCD. Undoubtedly, to solve this problem, it is necessary to search for the effects with large discrepancies between these approaches.

On the other hand, the investigation [3] of correlators of quark currents beyond the framework of operator expansion - the basis of the well-known sum rules of QCD (e.g. using instantons), indicates that one can distinguish three space regions in hadrons: at $r \lesssim \rho_c \approx \frac{1}{3} fm$ the operator expansion and perturbation theory (current quarks) are applicable; in the region $\rho_c \lesssim r \lesssim R_c$ (R_c is confinement radius) the quarks become "dressed" and massive (constituents, "additive" quarks); at $r \gtrsim R_c$ an hadron is formed with observed mass and other static and dynamical properties. Within this picture, ρ_c appears to be a characteristic scale of vacuum fluctuations, suppressing nonperturbative contributions.

From this point of view, the experiments on deep inelastic processes are surely related to the first region in the hadron. As to the second region ($\rho_c \lesssim r \lesssim R_c$), it follows from obvious motivations that "enlightenment" of the nucleon by means of low and intermediate energies allows to feel its inner degrees of freedom connected with constituent quarks.

In this connection, the application of well-known in atomic and nuclear physics sum rules to quasi-nuclear systems like which hadrons appear in the mentioned second region ($\rho_c \lesssim r \lesssim R_c$) is highly interesting. This point is not a new one, it was faced with some twenty years ago [4]. When measuring photoabsorption cross sections on quantum systems, one can draw. generally speaking, nontrivial conclusions about the structure and parameters of the ground state of the systems.

Quite surprising is the fact that these sum rules which are based not only on the assumption about the system nonrelativism but also on the long-wave approximation, "work" well when describing photoabsorption on nuclei as systems of nucleons and hadrons consisting of quarks.

At present, owing to rich and sufficiently qualitative experimental material on photoproduction of particles on protons, one can draw more definite conclusions about the main characteristics of the nucleon as a bound state of the quark system.

2. Sum Rule of Zero Moment σ_0 (E 1).

Let us consider the sum rule for electric dipole photoabsorption on the nucleon, analogous to the classic sum rule of Thomas-Reiche-Kuhn, which can be written in CQM terms in the following way:

$$\sigma_0(E1)=\int_0^{\infty}\sigma_{E1}(\omega)\,d\omega=\frac{2\pi^2}{m_q}(q_u-q_d)^2\,\frac{N_u N_d}{N_u+N_d} \qquad (1)$$

where q_u and q_d are charges of u and d quarks, m_q is their mass, N_u and N_d is number of u and d quarks in the nucleon.

This sum rule may be generalized taking into account nucleon recoils. With this aim, let's write down the total electric dipole absorption cross section on the nucleon in the c.m.s. in the form [4]:

$$\sigma_{E1}(\omega)=4\pi^2\sum_f\frac{M_N(W^2-M_N^2)}{2W^2}\left|\langle f|\vec{\varepsilon}\cdot\hat{\vec{\mathcal{D}}}|0\rangle\right|^2\delta(W-E_f)\prod_f\frac{d^3P_f}{(2\pi)^3} \qquad (2)$$

where M_N is nucleon mass, $\vec{\varepsilon}$ is the photon polarization vector, W total energy of the system γN, $\hat{\vec{\mathcal{D}}}$ is dipole moment operator; summation is carried out over all variables of final states with total energy E_f, and integration over momentum of one of the final particles is carried out in the phase space. Let's integrate both sides of Eq.(2), multiplying them beforehand by $\frac{2W^2}{M_N(W+M_N)}$, which allows to present the integral from the right-hand side as

$$4\pi^2\sum_f(E_f-E_0)\left|\langle f|\hat{\mathcal{D}}_z|0\rangle\right|^2=2\pi^2\langle 0|[\hat{\mathcal{D}}_z,[\hat{H},\hat{\mathcal{D}}_z]]|0\rangle \qquad (3)$$

where we have assumed that the photon polarization vector $\vec{\varepsilon}$ is directed along the Z axis and where we have used the completeness of $|f\rangle$ functions system. After some simple transformations, assuming that quarks in the nucleon are nonrelativistic and that the interaction between them is of two-particle character, we get the following sum rule:

$$\sigma_0(E1) \equiv \int_0^\infty \frac{2\sqrt{1+\frac{2\omega}{M_N}}}{1+\sqrt{1+\frac{2\omega}{M_N}}}\,\sigma_{E1}(\omega)d\omega = \frac{2\pi^2}{m_q}(q_u - q_d)^2\,\frac{N_u N_d}{N_u + N_d} \qquad (4)$$

where the integration is carried out over photon energy in the lab. coordinate system.

Below, we shall consider the both expressions (1) and (4) for the sum rule σ_0 . This is due to the fact that, as mentioned, in the basis of sum rules there lies not only the assumption about the system nonrelativism, but also the long-wave approximation, which is broken in the main region of the integration. Therefore corrections to the sum rule (1) do not reduce to the account of nucleon recoil only.

Let's saturate the sum rules (1) and (4) for protons making use of experimental data available. In the channel $\gamma p \to \pi N$ the experimental data in the energy range from the threshold to 1.2 GeV allow one to isolate reliably the electric dipole absorption cross section. The value of this cross section, including the resonance and background contributions, we have taken into account in accordance with the phenomenological analysis [5] . In this energy range we took into account also all the resonance contributions into other channels of the reaction of photoabsorption on nucleon. With this aim, the resonance production cross sections in the reactions $\gamma p \to N^*$ were expressed through the widths of $N^* \to N\gamma$ decays:

$$\sigma(\gamma N \to N^*) = \frac{\pi^2}{2}(2s+1)\,\frac{W\Gamma(N^* \to N\gamma)}{\omega_c^2\sqrt{M_N^2+\omega_c^2}}\,\delta(\omega - M) \qquad (5)$$

where ω_c is photon energy in the c.m.s. γN , S and M are spin and mass of the resonance. Using the formulae from [6,7], the $N^* \rightarrow N\gamma$ decay width corresponding to the electric dipole transition can be expressed through generally accepted amplitudes $A_{1/2}$, $A_{3/2}$ [6] which are well determined from the analysis of $\gamma p \rightarrow \pi N$ reaction. As a result, for the resonances with spins 1/2 and 3/2 we obtain

$$\Gamma_{E1}(N^* \rightarrow N\gamma) = \frac{\omega_c^2}{\pi} \frac{M_N}{M} |A_{1/2}|^2 \qquad (6a)$$

$$\Gamma_{E1}(N^* \rightarrow N\gamma) = \frac{3\omega_c^2}{8\pi} \frac{M_N}{M} \left| A_{3/2} + \frac{A_{1/2}}{\sqrt{3}} \right|^2 \qquad (6b)$$

To avoid the double account of the resonance contributions in $\gamma p \rightarrow \pi N$ channel, the cross sections (5) were multiplied by a coefficient $1-\eta$ where $\eta = \frac{\Gamma(N^* \rightarrow N\pi)}{\Gamma_{tot}(N^*)}$.

The results of the calculations for the photoabsorption on the proton with account of the contributions up to the 1.2 GeV region are given in Table 1. In addition, the Table gives separately the values of the contributions to $\gamma p \rightarrow \pi N$ channel and those of the resonance contributions to other channels of the reaction of photoabsorption on the proton. The contribution for the energies above 1.2 GeV cannot be evaluated at present, however it may turn out not negligible, for as seen from Fig.1, the photoabsorption cross section for the proton decreases rather slowly. This contribution being neglected, the sum rule (1) (see Table 1) holds well at $m_q = M_N/3$. As to the sum rule (4), which takes into account the nucleon recoil, for its fulfilment, as seen from the Table, a somewhat smaller value of the constituent quark mass m_q is needed. If the contribution of the energy range higher than 1.2 GeV turns out essential, in this case also the smaller mass of the quark will be required to fulfil the sum rule (1) *).

As seen from the sum rules (1) and (4), the quark model predicts quite definitely the equality of the left-hand sides for the photoabsorption on proton and neutron.

The experimental data available do not allow to execute a detailed analysis, analogous to the one performed above, for photoproduction on the neutron. Nevertheless, in the sum rules for protons and neutrons one can isolate and compare the main contributions the Born terms in $\gamma N \rightarrow \pi N$ channel and $S_{11}(1535)$, $D_{13}(1520)$ and $D_{33}(1670)$ resonances contributions refer to.

One can readily see that the Born contributions determined mostly by the pion pole in $\gamma p \rightarrow \pi^+ n$ and $\gamma n \rightarrow \pi^- p$ reactions nearly coincide for protons and neutrons.

The contributions into total photoabsorption cross section of D_{33} resonance are equal for protons and neutrons. As to S_{11} and D_{13} resonances, which can be excited by both the isovector and isoscalar photon, the equality of the photoabsorption cross sections on the proton and neutron is, generally speaking, not obvious. However CQM predicts nearly coinciding values for these quantities and this is confirmed by the experiment (see, e.g. [5]).

Thus the main contributions into the integrals of (1) and (4) for the proton and neutron are close to each other in accordance with the sum rules (1) and (4). This makes the task of bringing the quality of the experiments on photoabsorption on the neutron in the resonance region to the level of the corresponding experiments on the proton highly important.

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*) In the recent work [14] , to bring CQM into agreement with the new data on baryon magnetic moments, the effective mass of constituent quarks also had to be reduced by the value of 15%. Ref.[14] suggests an idea that "feeling" hadrons by long-wave photons points out smaller (peripheral) mass of the quark.

3. Sum Rule $\sigma_{-1}(E\,1)$.

Let's proceed to the comparison of the experiment with the sum rule [10]

$$\sigma_{-1}(E1)=\int\limits_0^\infty \frac{\sqrt{1+\frac{2\omega}{M_N}}}{\omega}\,\sigma_{E1}(\omega)\,d\omega=\frac{4\pi^2}{3}\langle 0|\hat{\vec{\mathcal{D}}}^2|0\rangle \tag{7}$$

and also with the analogous sum rule without account of the nucleon recoil.

Taking into account the fact that for nucleons consisting of nonrelativistic quarks, the dipole moment operator has the form of

$$\hat{\vec{\mathcal{D}}}=\sum_{i=1}^{3} q_i\,\vec{r}_i \tag{8}$$

it is easy to get for the proton

$$\langle 0|\hat{\vec{\mathcal{D}}}^2|0\rangle = e^2\langle p|\vec{r}_d^{\,2}|p\rangle \tag{9}$$

where $\vec{r}_d$ is the vector radius of d -quark in the c.m.s. of the proton.

In case the nucleon is a pure $[56,0^+]$ state, the mean $\vec{r}_d^{\,2}$ in the proton coincides with the mean-square radius $\langle r^2\rangle_{ch}^{p}$ of charge distribution in the proton:

$$e^2\langle p|\vec{r}_d^{\,2}|p\rangle_{p\in[56,0^+]}=\sum_i\langle p|e_i^2 r_i^2|p\rangle=e^2\langle r^2\rangle_{ch}^{p} \tag{10}$$

But if one takes into account the $[70,0^+]$ multiplet admixture in the nucleon, which is indicated at by the mass formulae for baryons with account of gluon interactions between quarks [11,12] , then the relation (10) is broken. In the general case, when the nucleon is a mixture of $[56,0^+]$, $[56,0^+]_r$ and $[70,0^+]$ states

$$|N\rangle = \sqrt{1-\cos^2\theta-\cos^2\varphi}\,|56\rangle + \sin\theta\,|56\rangle_r + \sin\varphi\,|70\rangle \tag{11}$$

we have:

$$\langle p|\vec{r}_d^{\,2}|p\rangle = X\langle r^2\rangle^p_{ch}\,, \tag{12}$$

$$X = \frac{\alpha+\beta}{\alpha-\beta}$$

$$\alpha = \cos^2\varphi\left(\cos^2\theta + \frac{2}{\sqrt{3}}\cos\theta\sin\theta + \frac{1}{6}\sin^2\theta\right) + \frac{5}{3}\sin^2\varphi \tag{13}$$

$$\beta = \frac{\sin 2\varphi}{\sqrt{6}}\left(\cos\theta + \frac{2}{\sqrt{3}}\sin\theta\right)$$

The mixing angles θ and φ are determined in the quark model :

$$\sin\theta = -0.34\,, \qquad \sin\varphi = -0.27 \quad [11] \tag{14}$$

$$\sin\theta = -0.24\,, \qquad \sin\varphi = -0.2 \quad [12] \tag{15}$$

Note by the way that the value of φ obtained from the mass formulae results in nonzero value of the neutron charge radius:

$$\frac{\langle r^2\rangle^n_{ch}}{\langle r^2\rangle^p_{ch}} = \frac{\beta}{\alpha-\beta} = \begin{cases} -0{,}16 & [11] \\ -0{,}14 & [12] \end{cases} \tag{16}$$

which in value and sign agrees well with the experiment:

$$\left.\frac{\langle r^2\rangle^n_{ch}}{\langle r^2\rangle^p_{ch}}\right|_{\text{эксп.}} = -0{,}15 \pm 0{,}01 \qquad (17)$$

As to the sum rule (7), the account of the $[70,0^+]$ multiplet admixture in the nucleon with the mixing angle (14), (15) leads to sufficient reduction in the right-hand side of Eq.(7):

$$X = \begin{cases} 0.68 & [11] \\ 0.72 & [12] \end{cases},$$

this providing (see Table 2) a better fulfilment of the sum rule (7) without introducing any significant radii of quarks [10] , which seems to be artificial.

Emphasize that in CQM the sum rule $\sigma_{-1}(E1)$ leads, just as in case with $\sigma_0(E1)$, to the equality of the integrals in the left-hand sides of Eq.(7) for the proton and neutron.

The above-quoted considerations, confirming this equality for the case with σ_0 , are true here too.

In conclusion, the authors would like to express their thanks to S.B.Gerasimov for the useful discussions and correspondence.

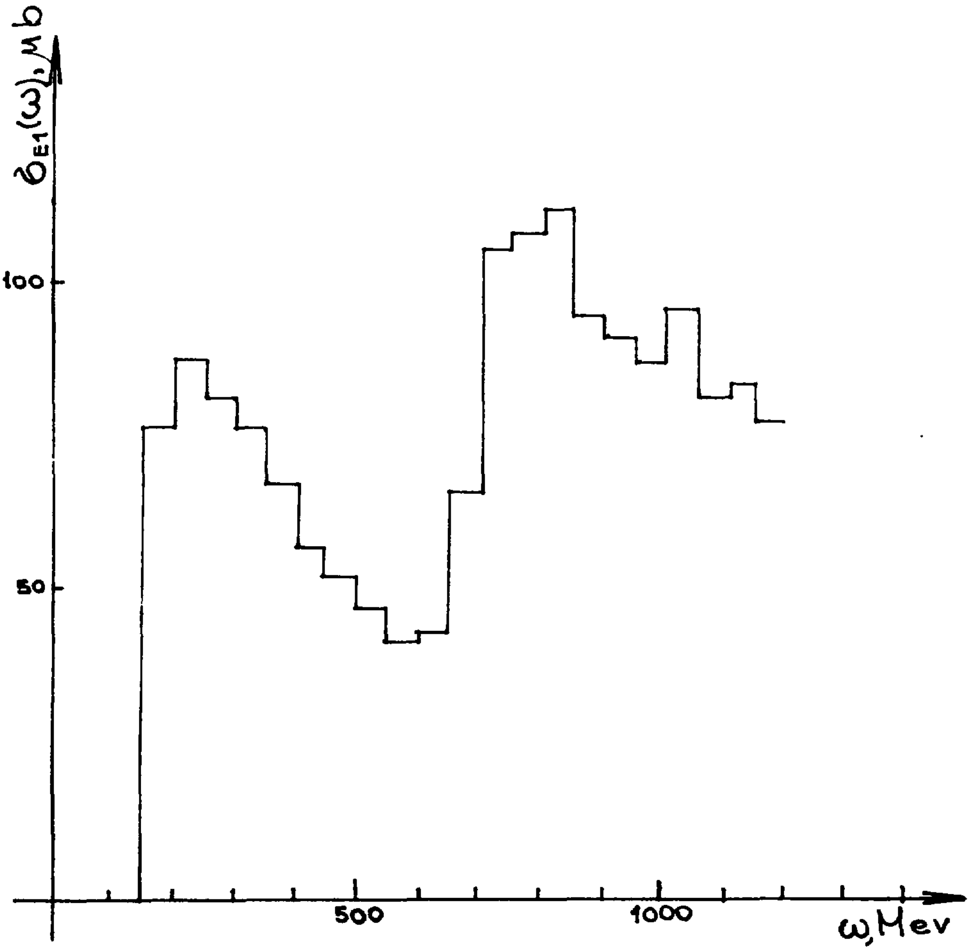

Fig.1. Energy dependence of the total cross section of E 1 photoproduction of single pions on proton.

Table 1. Sum rule σ_0 (E 1) for photoabsorption on proton.

	Contribution of the energy range up to 1.2 GeV into the l.h.s. of the sum rule			The r.h.s. of the sum rule
	Channel $\gamma p \to \pi N$	Resonance contributions into other channels	Summary contribution	
Without recoil	0.08±0.02	0.04±0.01	0.12±0.02	0.12 $\frac{M_N}{3m_q}$ ($M_N/3m_q$ = 1 in nonrelativistic quark model)
With recoil	0.10±0.02	0.05±0.01	0.15±0.02	

Note: all the values are given in the units of MeV bn.

Table 2. Sum rule σ_{-1}(E 1) for photoabsorption on proton.

	Contribution of the energy range up to 1.2 GeV into the l.h.s. of the sum rule			The r.h.s. of the sum rule	
	Channel $\gamma p \to \pi N$	Resonance contributions into other channels	Summary contribution	Without mixing	With multiplets $[70,0^+]$, $[56,0^+]$ admixture [11]
Without recoil	0.18±0.04	0.05±0.01	0.23±0.04	0.64	0.44
With recoil	0.23±0.04	0.08±0.02	0.31[illegible]0.05		

Note: all the values are given in the units of mbn. In the calculation of the right-hand side of the sum rules the experimental data of [13] have been used.

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ЭЛЕКТРИЧЕСКОЕ ДИПОЛЬНОЕ ФОТОПОГЛОЩЕНИЕ И КВАРКОВАЯ СТРУКТУРА НУКЛОНОВ

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