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ON THE Q^2 VARIATION OF SPIN-DEPENDENT DEEP-INELASTIC ELECTRON PROTON SCATTERING

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Abstract

We suggest a phenomenological model describing the sum rules for the real and virtual polarized photon absorption on the nucleon. The contribution of the isobar Δ (1232) electroproduction, essential at small Q^2, has been subtracted quantitatively. The model predictions are compared with the results of the EMC polarized structure function measurements on the proton.

In the past few years there have been wide-spread discussions of the EMC results on the deep-inelastic scattering of polarized muons on polarized protons[1],[2]. The spin-dependent structure function of the proton $g_1(x)$ has been measured in these experiments and, using earlier SLAC data [3] it was found that at $\bar{Q}^2 = 10.7\ \mathrm{GeV}^2$.

$$\Gamma_p(\bar{Q}^2) = \int_o^1 dx\ g_1(x, \bar{Q}^2) = 0.126 \pm 0.010 \pm 0.015 \tag{1}$$

Theoretically, the expected value of $\Gamma_p(Q^2)$ may be determined from the Ellis-Jaffe (EJ) sum rule [4] obtained under the following assumptions: i) a nonpolarized strange sea in the nucleon; ii) exact SU(3) flavour symmetry in the matrix elements of the octet axial current between baryonic octet states. With the account of first order perturbative corrections [5] the theoretical expression for $\Gamma_p\ (Q^2)$ has the form

$$\Gamma_p(Q^2) = \frac{1}{12}\left\{g_A\left[1 - \frac{\alpha_s(Q^2)}{\pi}\right] + \frac{5}{3}(3F - D)\left[1 - \frac{1}{5}\left(1 + 4\frac{33 - 8f}{33 - 2f}\right)\frac{\alpha_s(Q^2)}{\pi}\right]\right\} \tag{2}$$

where F and D are the β - decay constants in the baryonic octet, f is the number of flavours, f = 3. The 3F-D value which follows from the hyperon β-decay [6] (see also [7], [8]) is

$$3F - D = 0.60 \pm 0.10 \tag{3}$$

(the error in (3) takes into account the spread in 3F-D arising when finding this value from various β - decays - see the discussion of this problem in [9]). Substituting $g_A = 1.254 \pm 0.006$, $\alpha_s\ (\bar{Q}^2) = 0.27$ and (3) into (2), we find

$$\Gamma_p(\bar{Q}^2)_{\text{theor}} = 0.175 \pm 0.013 \tag{4}$$

Theoretical and experimental values of $\Gamma_p(\bar{Q}^2)$ are in contradiction. A number of attempts were made to solve the discrepancy. Not dwelling into discussion of a lot of the literature on this problem we will consider in this paper one of these attempts [9] to attribute the discrepancy between (3) and (4) to the nonperturbative Q^2 dependence of the corresponding sum rules.

The main idea of the paper [9] (see also the earlier discussion of this question in the book [10], pp. 143, 255) was that the sum rule for the integral over x from the structure function g_1(x) in the scaling region is connected with the Gerasimow-Drell-Hearn (GDH) sum rule [11,12] for the forward scattering amplitude of the polarized (real) photon on the polarized proton. Namely, if we denote

$$I_p(Q^2) = \int_{Q^2/2}^{\infty} \frac{d\nu}{\nu}\ G_1^p(\nu, Q^2)\ \equiv \frac{2m_p^2}{Q^2}\ \Gamma_p(Q^2) \tag{5}$$

where ν = pq, q- is the photon momentum $q^2 = -Q^2$, p - is the proton momentum, $G_1(\nu, Q^2)$ - is the spin-dependent proton structure function. Making use of the relation

$$\lim \frac{\nu}{m_p^2}\ G_1^p(\nu, Q^2)|_{\substack{\nu \to \infty \\ Q^2/2\nu = x - \text{const}}} = g_1(x, Q^2) \tag{6}$$

it can be easily shown that in the scaling limit $\Gamma_p(Q^2)$ in (5) coincides with that defined in (1). The value of $I_p(0)$ is given by the GDH sum rule:

$$I_p(0) = -\frac{1}{4}\kappa_p^2 \tag{7}$$

where κ_p= -1.79 is the proton anomalous magnetic moment.

As follows from [5], [7] the integral $I_p(Q^2)$ changes dramatically as Q^2 increase: at $Q^2 = 0$ it is negative and its absolute value is large while at large Q^2 it is positive, rather small and decreases with Q^2. Such a behaviour, which, evidently cannot be described in the framework of perturbative QCD, shows that nonperturbative effects in $I_p(Q^2)$ dominate in the region of small and possibly intermediate Q^2. An attempt was made in Ref. [9] to describe the behaviour of $I_p(Q^2)$ throughout the whole region of Q^2 with help of a phenomenological model, based on the idea of the vector dominance model (VDM). In doing so the difference between experimental (1) and theoretical values of $\Gamma_p(\bar{Q}^2)$ was attributed to higher twist terms, i.e. it was assumed that the mean value $Q^2 = 10.7$ GeV in the EMC experiment is not yet asymptotic. After the publication of [9], in a more detailed EMC paper [2] the model [9] was compared with the EMC and SLAC data and it was shown that it contradicts the experiment by 1.5 standard deviations.

However, when constructing the model, the authors of [9] did not take into account an important circumstance. At $Q^2 = 0$, the main fraction (more than 80%) in the GDH sum rule integral (5) is given by the contribution of the isobar Δ (1232) photoproduction (see [12],[13], [14]). At $Q^2 = 0$, this contribution is negative while at large Q^2 it must become positive and decreases rapidly with increasing Q^2. These statements can be easily understood based on general considerations connected with restoration of the chiral invariance at large Q^2 [15], [10]. Indeed, eq. (5) can be also written as

$$I_p(Q^2) = \frac{m_p^2}{8\pi^2\alpha}\int_{Q^2/2}^{\infty}\frac{d\nu}{\nu}\left[\sigma_{\frac{1}{2}}(\nu,Q^2) - \sigma_{\frac{3}{2}}(\nu,Q^2)\right] \tag{8}$$

where $\sigma_{\frac{1}{2}}$, $\sigma_{\frac{3}{2}}$ are photoabsorption cross sections, corresponding to projections 1/2 and 3/2 of the photon and the proton total spin to the photon momentum direction. At small Q^2 the magnetic dipole transitions dominates $\Delta(1232)$ photoproduction, and $\sigma_{\frac{3}{2}}/\sigma_{\frac{1}{2}} \approx 3$ (see [14]). At large Q^2, because of chiral invariance only $\sigma_{\frac{1}{2}}$ survives [15, 10] and the Δ (1232) contribution changes its sign. Since the formfactor of the $p \to \Delta$ transition decreases rapidly with Q^2, the Δ (1232) contribution to the electroproduction cross section will be negligible at large Q^2, and its contribution should be excluded when constructing a model based on VDM. (The same consideration refers also to other resonances, in particular, to $N^*(1520)$. However, since their contributions to the GDH sum rule are small we neglect them when constructing our model.)

Therefore, we modify the model suggested in Ref. [9] and put

$$I_p(Q^2) = I_{p\Delta}(Q^2) + 2m_p^2\Gamma_p^{as}\left[\frac{1}{Q^2+\mu^2} - \frac{c\mu^2}{(Q^2+\mu^2)^2}\right] \tag{9}$$

where $I_{p\Delta}(Q^2)$ is the contribution of Δ (1232), Γ_p^{as} is the asymptotic value of $\Gamma_p(Q^2)$ at large Q^2, where the higher twist terms are neglected, μ is the mass parameter characterizing the model. In what follows we will use $\mu = m_\rho$. The constant c is chosen from the requirement that the GDH sum rule must be fulfilled at $Q^2 = 0$, i.e.

$$c = 1 + \frac{1}{2}\frac{\mu^2}{m_p^2}\ \frac{1}{\Gamma_p^{as}}\left[\frac{1}{4}\ \kappa_p^2 + I_{p\Delta}(0)\right] \tag{10}$$

Using the experimental data on Δ (1232) photoproduction (see Ref. [14]), we find

$$\frac{1}{4}\kappa_p^2 + I_{p\Delta}(0) \approx 0.026 \tag{11}$$

and

$$c \approx 1.05 \tag{12}$$

The Q^2 dependence of the GDH-EJ sum rules in our model is presented in Fig. 1, the isobar Δ (1232) contribution was taken from Ref. [14]. Our model predicts a sign change of $\Gamma_p(Q^2)$ at $Q^2 \sim 0.8 GeV^2$. This sign change has to occur in order to accomodate the GDH sum rule limit at $Q^2 = 0$.

At $Q^2 = 10.7$ GeV^2 - the mean Q^2 in the EMC experiment - $\Gamma_p(Q^2)$ differs from $\Gamma_p^{as}(Q^2)$ in our model by 10% due to the power corrections. Thereby, in the difference

$$\Delta\Gamma_p = \Gamma_p(Q^2)_{theor} - \Gamma_p(Q^2)_{exp} \approx 0.050 \tag{13}$$

about 0.010 may be attributed to the contribution of higher twist terms. This amount of power corrections does not contradict the EMC data. In order to check the Q^2 dependence of $\Gamma_p(Q^2)$ the EMC data were divided in Ref. [2] into two intervals and it was found that $\Gamma_p = 0.130 \pm 0.015 \pm 0.018$ at $Q^2 = 4.8$ GeV^2, and $\Gamma_p = 0.114 \pm 0.021 \pm 0.019$ at $Q^2 =$ 17.2 GeV^2. In our model, if, for example, the normalization to the experimental value Γ_p = 0.114 at $Q^2 = 17.2$ GeV^2 would be used, then at $Q^2 = 4.8$ GeV^2 we would have $\Gamma_p =$ 0.095. This value is not in contradiction with the EMC experiment bearing in mind the errors at both points in Q^2.

The twist-4 corrections to the sum rules for deep-inelastic scattering on polarized isovector (p-n, the Bjorken sum rule) and isoscalar (p+n) nucleon target were calculated in Ref. [16] (see also [8]). The magnitudes of corrections are essentially smaller - about three times - than in our model. The calculations were performed using the QCD sum rule method for the problem in external constant field. However, as was shown in [17] this method is inapplicable for problems with external singlet axial field and, particularly, for determining the g_A^s constant of the proton-singlet axial current interaction. Namely, vacuum condensates induced by the singlet external field A_μ^s arise in this problem. In the calculation of such vacuum condensates of importance is the axial anomaly what was not taken into account in Ref. [16].

Since in the case of the sum rule for a proton target the twist-4 corrections are determined by the proton matrix element from the current with the same quantum number as A_μ^s, we think that the calculation of Ref. [16] are unreliable. In addition, the fitting procedure is not demonstrated in Ref. [16] and it is unclear if both necessary requirements of the QCD sum rule approach - the simultaneous smallness of higher order terms in OPE and the continuum contribution are fulfilled. Note that for the Bjorken sum rule (where the Δ (1232) contribution is absent because of isotopic invariance [10]), our model, which coincides with [9], gives excellent interpolation between large Q^2 and the point Q^2=0, while in the calculation of Ref. [16] noticeable deviations from the interpolation curve arise at $Q^2 = 3$ GeV^2, where twist-4 corrections are yet small. The final judge in this problem must be, naturally, the experiment.

Note in conclusion, that if, in accordance with our model, the higher twist contribution comprises 0.010 in the difference between theoretical and experimental values of Γ_p, $\Delta\Gamma_p$

= 0.050, the gluon contribution [5, 18-22]

$$\Delta\Gamma_p^g = -\frac{\alpha_s}{6\pi}\Delta g \tag{14}$$

even at a conservative estimate of Δg $\sim$ 0.5-1 may be of the order of magnitude -0.01, and the contribution of the strange sea could be -0.003, then even a small excess of the data over experimental errors will be sufficient for the disagreement between theory and experiment to disappear.

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Figure Caption

Figure 1: The sum rule integral $\Gamma_p(Q^2)$ in our model. The solid line includes the contribution from the p$\Delta(1232)$ isobar transition, the dashed line is without the $\Delta(1232)$ contribution. The dotted line includes an estimated gluon contribution of -0.01, and a strange quark contribution of -0.003. The short dashed line represents the original Ellis-Jaffe sum rule with lowest order perturbative QCD corrections (eqn.(2), with $\Lambda^{QCD} = 250MeV/c$). The data are the Q^2 averaged EMC data at $\bar{Q}^2 = 4.8GeV^2$ and at $\bar{Q}^2 = 17.2GeV^2$; the error bars include statistical (inner bars) and systematical (outer bars) uncertainties.

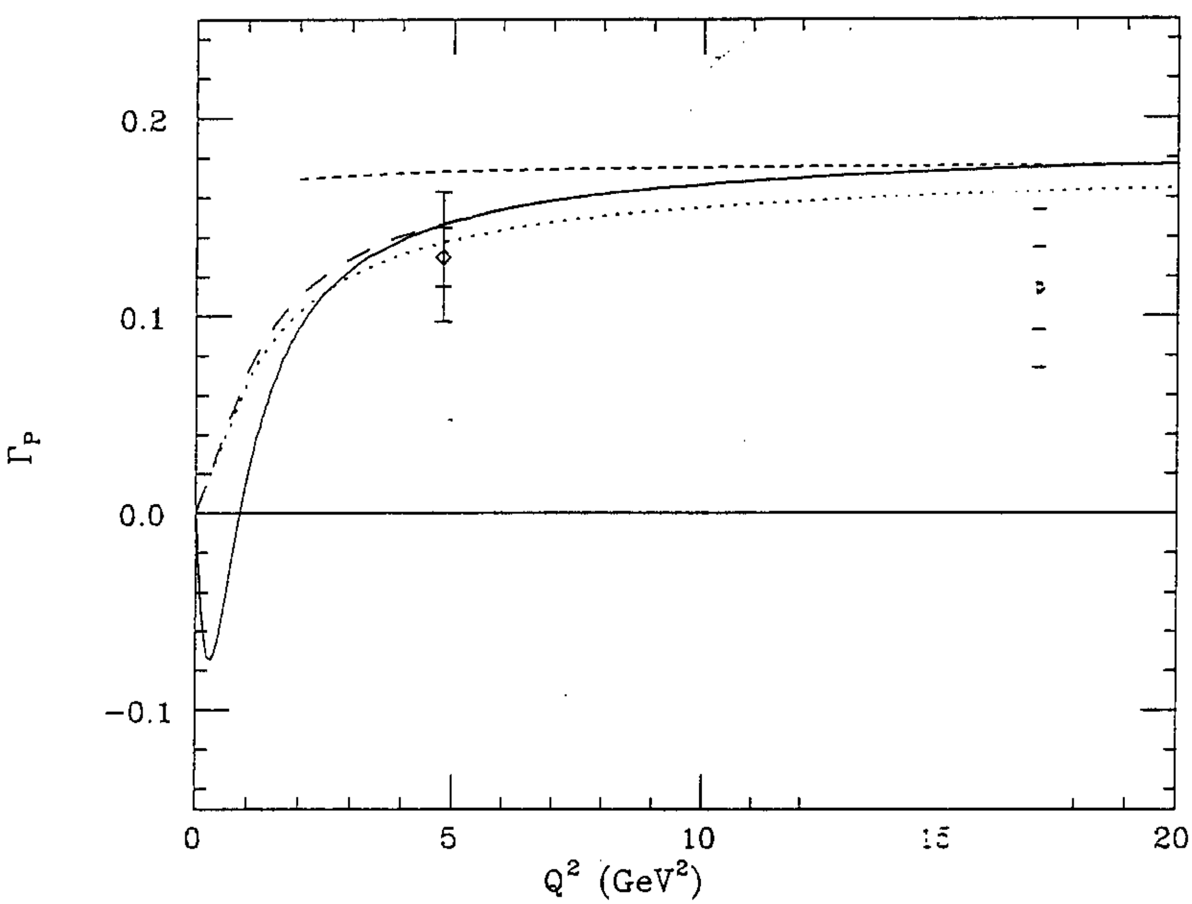

Figure 1