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SPIN-DEPENDENT STRUCTURE FUNCTIONS OF SEA QUARKS IN THE FRAMEWORK OF NONPERTURBATIVE QCD AND NEW REGGE TRAJECTORY

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Recently the experimental data of extreme importance concerning the sea quark structure function measurements have been appeared[1]–[3],*) The EMC group[1] has measured the DIS proton spin-dependent structure function , $g_1^p(x)$, with high accuracy. The data analysis has given the following estimation of the helicity carried by sea quarks:

$$\Delta u^s + \Delta d^s + \Delta s^s = -0.95 \pm 0.16 \pm 0.23, \quad (1)$$

where

$$\Delta q^s = \int_0^1 dx\, [q_+^s(x) - q_-^s(x)],$$

$q_+^s(x)(q_-^s(x))$ being the quark of flavor q distribution with the helicity parallel (antiparallel) to the parent helicity of the proton.

The independent estimation for the helicity of strange quarks obtained from the neutrino experiment[2] is as follows:

$$\Delta s^s = -0.15 \pm 0.09. \quad (2)$$

Thus, the contributions of sea quarks to the proton helicity can be deduced

$$\Delta u^s \approx \Delta d^s \approx -0.4;\ \Delta s^s \approx -0.15. \quad (3)$$

These values are about one order higher than the fractions of the proton momentum carried by sea quarks[3]:

$$u^s \approx d^s \approx 0.05;\ s^s \approx 0.02, \quad (4)$$

where $q^s = \int_0^1 dx\, [q_+^s(x) + q_-^s(x)]$. The anomalously large contribution of sea quarks to the proton helicity has given rise to the so-called "spin crisis" (see for the details[4]) because it cancels almost completely the helicity carried by valence quarks.

In our works[5] (see also[6]) the nonperturbative mechanism of appearance of the negative helicity of sea quarks has been suggested. It is based on the model of the QCD vacuum as an instanton liquid[7]. The matter is that in an instanton field, a strong nonperturbative gluon fluctuation, a quark being in the t'Hooft zero mode[8] changes its chirality to the opposite one. This phenomenon is quite analogous to the appearance of the baryon number from the Dirac vacuum in the field of a strong topological fluctuation of the chiral field in the Skyrme-like models of the nucleon[9].

In the recent paper[10] the idea of works[5, 6] on a dominant role of the instanton mechanism in arising the helicity of sea quarks has been used to construct manifestly the quark structure functions. Therein, within the dilute instanton gas approximation the contribution of instantons into the proton axial form factor has been determined (fig. 1) as follows:

$$G_A^5(Q^2) \propto (1/Q^2)^n, \quad n \geq 5. \quad (5)$$

Then, by using the Drell-Yan-West relation one can derive the x-dependence of the polarized structure functions:

$$\Delta q(x) \approx B(1-x)^p, \quad p \geq 10. \quad (6)$$

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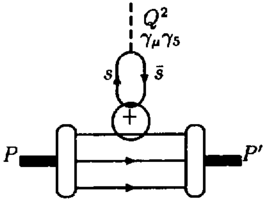

Fig. 1. The instanton contribution to the proton axial form factor (+(−)-(anti)instanton).

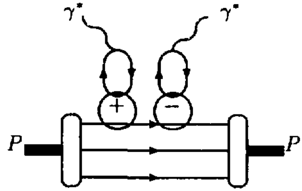

Fig. 2. The instanton contribution to the DIS structure function obtained from Drell-Yan-West relation[10].

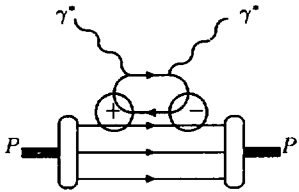

Figure 3. The leading twist contribution to the sea structure functions.

Note, that the Drell-Yan-West relation is obtained as a result of squaring of the diagram of Fig. 1 (see Fig. 2). Evidently, then a large momentum passes through a non-perturbative fluctuation leading to a very strong Q^2- dependence ($\Delta q(x) \propto (1/Q^2)^{2n}$) of the structure function Eq. (6). This means that expression Eq. (6) probably bears no relation to the structure function of leading twist.

The lowest diagram contributing into the sea quark structure function of the leading twist is depicted in Fig. 3. The quark distributions are connected with the wave function on the light cone by the relation[11]:

$$q_{f/p}(x) \propto \sum_n \int [dk_{\perp i}][dx_i]\ \delta(x - x_q) \cdot \mid \Psi_{(n)}(k_{\perp i}, x_i) \mid^2 \cdot \Theta(k_{\perp i}^2 \leq Q^2), \qquad (7)$$

where $\Psi_{(n)}(k_{\perp i}, x_i)$ is the contribution of an n-particle intermediate state to the wave function, $x_i = (k^0 + k^3)_i/(p_0 + p_3)$, $\sum_{i=1}^n \vec{k}_{\perp i} = 0$, $\sum_{i=1}^n x_i = 1$. The most general form of the wave function is[11]:

$$\Psi_{(n)}(k_{\perp i}, x_i) = \frac{\Gamma_n(k_{\perp i}, x_i)}{M_p^2 - \sum_{i=1}^{n} \frac{m_i^2 + k_{\perp i}^2}{x_i}} \quad . \tag{8}$$

Within the model of the QCD vacuum as an instanton liquid[7] $\Gamma_n(k_{\perp i}, x_i)$ are the form factors of quarks in the instanton field which depend exponentially on quark virtualities, so

$$\Psi_{(n)}^{inst}(k_{\perp i}, x_i) \propto \frac{\exp\{-\frac{\rho_c}{p_+}(M_p^2 - \sum_{i=1}^{n} \frac{m_i^2 + k_{\perp i}^2}{x_i})\}}{M_p^2 - \sum_{i=1}^{n} \frac{m_i^2 + k_{\perp i}^2}{x_i}} \quad . \tag{9}$$

In the integral Eq. (7) the dominant region is

$$M_p^2 \approx \sum_{i=1}^{n} \frac{m_i^2 + k_{\perp i}^2}{x_i}. \tag{10}$$

Then, one can put down with high accuracy :

$$q_{f/p}(x) \propto A \int \frac{[dx_i]\delta(x - x_q)}{| M_p^2 - \sum_{i=1}^{n} \frac{m_i^2 + < k_\perp >^2}{x_i} |^2}. \tag{11}$$

It should be noted that such nonperturbative quark distributions provide at $m_i^2, < k_\perp^2 > \ll M_p^2$ correct behavior of the valence quark distributions of mesons $(1-x)^2$ and baryons $(1-x)^3$ as $x \to 1$[11].

For the sea distributions of light (u, d, s) and heavy (c, b) quarks we obtain from Eq. (11) :

$$\begin{aligned} q_{f/p}^s(x)_{x \to 1} &\propto (1-x)^5, \quad q = u, d, s; \\ q_{f/p}^s(x)_{x \to 1} &\propto (1-x)^3, \quad q = c, b. \end{aligned} \tag{12}$$

The behavior as $x \to 0$ is specified by Regge asymptotics. Usually one assumes (see [12]) that the Pomeron exchange with $\alpha_p \approx 1$ dominates in the sum $q^s(x) = q_+^s(x) + q_-^s(x)$, and, hence:

$$\lim_{x \to 0} q^s(x) \propto 1/x, \tag{13}$$

whereas the difference $\Delta q^s(x) = q_+^s(x) - q_-^s(x)$ is specified by the A_1-meson contribution ($\alpha_{A_1} \approx 0$), and, so

$$\lim_{x \to 0} \Delta q^s(x) \propto const. \tag{14}$$

Usually in order to argue Eq. (14)[10, 12, 13] one says that the trajectories with the quantum numbers $\sigma(-1)^I G = -1$ (σ is signature), A_1 being the well-known example with $I = 1$, $\sigma = -1$, $G = -1$ contribute into $\Delta q(x)$. However, to our opinion, such reasoning is not quite correct, because A_1 (the trajectory with $I = 1$) can not contribute into the isosinglet anomalous combination $\Delta u + \Delta d + \Delta s$. The only trajectory capable to contribute into $\Delta q = \Delta u + \Delta d + \Delta s$ is the trajectory with $I = 0$, $\sigma = -1$, $G = 1$.

In our model of the structure functions of sea quarks Eqs. (16) this trajectory has to have large intercept $\alpha = 1 - \epsilon$, $\epsilon \ll 1$ in order to explain the difference by an order between the magnitudes of Eq. (3) and Eq. (4). It appears that like the Pomeron trajectory, this one does not correspond to any real particles but is the manifestation of nonperturbative properties of QCD. So in QCD, the Pomeron arises probably as a consequence of conformal anomaly[14] $< p \mid G^a_{\mu\nu} G^{a\mu\nu} \mid p > \neq 0$. A new trajectory is connected with Adler-Bell-Jackiw (ABJ) axial anomaly $< p \mid G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \mid p > \neq 0$ and, in particular, is manifested as a ghost pole in the form factor of singlet axial-vector current[15].

Naturally, ABJ trajectory should appear also in $pp-$ and $p\bar{p}-$ interactions . We note that to explain modern experimental data, some additional to the Pomeron trajectory is really needed which would not die out with energy and would dominate at large transfer $t \geq -1\ Gev^2$. Usually, this trajectory is identified with odderon[16], which has quantum numbers $\sigma = -1$, $P = -1$, ,$C = -1$. Within QCD odderon is expressed as three gluon exchange between nucleons.

However, there are two problems with practical application of odderon QCD to experimental data of $pp-$ and $p\bar{p}-$ interactions . Firstly, it needs the mechanism of odderon suppression at small t, otherwise it leads to nonvanishing difference of total cross sections $\sigma^{tot}_{pp} - \sigma^{tot}_{p\bar{p}}$ with energy $(\sqrt{s})$. Secondly, at large t radiation corrections to three gluon exchange give essential dependence of elastic $pp-$ and $p\bar{p}-$ interactions on $\sqrt{s}$[17] that is not visible in experiment.

To our opinion, ABJ trajectory gives more natural explanation of existing $pp-$ and $p\bar{p}-$ data.[†)] Thus, due to its quantum numbers it does not give any contributions to total cross sections. Further, at small t its contributions to elastic $pp-$ and $p\bar{p}-$ cross sections will be apparently proportional to the magnitude of singlet axial-vector form factor at zero $< p \mid G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \mid p > \propto \Delta u + \Delta d + \Delta s$ which is small[5, 18].

At large t the residue of Pomeron trajectory behaves as the nucleon electromagnetic form factor[19]. At the same time we think that the residue of ABJ trajectory will behave as the nucleon singlet axial-vector form factor. It is known[20], that this form factor falls off much slower than electromagnetic one. Thus, at large t ABJ trajectory has to dominate over Pomeron one. Independence of elastic cross sections at $t \geq -2\ Gev^2$ on $\sqrt{s}$[21] can be also lightly explained by very small slope $\alpha'_{ABD} \leq 0.1\ Gev^{-2}$ of ABJ trajectory.

So, we believe that ABJ trajectory dominates as at large t in elastic $pp-$ and $pp-$ interactions as in the difference of spin-dependent structure functions of sea quarks, and their asymptotic has a form:

$$\lim_{x \to 0} \Delta q^s(x) \propto 1/x^{1-\epsilon}, \quad \epsilon \ll 1. \tag{15}$$

†) The characteristics of $pp-$ and $p\bar{p}-$ interactions calculated with ABD trajectory will be published elsewhere.

Thus, the following parametrization of the distribution functions of sea quarks in the proton is proposed:

$$q_+^s(x) \approx \frac{B_q}{x^{1-\epsilon}}(1-x)^{k_q} + \frac{A_q}{2x}(1-x)^n, \qquad (16a)$$

$$q_-^s(x) \approx \frac{2B_q}{x^{1-\epsilon}}(1-x)^{k_q} + \frac{A_q}{2x}(1-x)^n, \qquad (16b)$$

where the latter terms describe the pomeron contribution as $x \to 0$ and the perturbative gluon one as $x \to 1$ ($n \approx 7$ within the quark-counting rule) and $k_q = 5$ for $q = u, d, s$; $k_q = 3$ for $q = c, b$.

The difference between the coefficients in Eq. (16a) and Eq. (16b) is due to the fact that sea quark helicity is antiparallel to the helicity of the valence quark off which the former is produced. In analogous manner, the substantial breakdown of $SU_f(2)$ and $SU_f(3)$ in the sea quark distribution functions, associated with the fact that the instanton-induced interaction is nonzero only for the quarks of different flavors, occurs. In the proton , for instance, the relation (in the first order in instanton interaction):

$$d_i^s(x) \approx 2u_i^s(x) \qquad (17)$$

is to be satisfied (sub i denotes instanton's contribution to Eq.16).

We should note, that the asymmetry of the sea Eq. (17) is not connected with the $u-$ and $d-$ quark mass difference. It arises as a consequence of a definite isospin structure of the proton wave function. Recently, the direct experimental evidences[22] of this asymmetry have appeared. There, it has been measured the value:

$$I = \int_0^1 dx\ [\bar{d}(x) - \bar{u}(x)] = 0.136\ \pm\ 0.06\,. \qquad (18)$$

In the framework of our model by using Eq.(16) this value can be related (in the limit of equal $u-$, $d-$ and $s-$ quark masses) to the chirality carried by sea quarks:

$$\int_0^1 dx\ [\bar{d}(x) - \bar{u}(x)] = -\frac{1}{4}(\Delta u^s + \Delta d^s + \Delta s^s)\,. \qquad (19)$$

Substituting Eq. (1) into Eq. (19) we have:

$$I \approx 0.24\ \pm\ 0.1\,. \qquad (20)$$

The difference between Eq. (20) and Eq. (18) arises most probably due to incorrect extrapolation of experimental data outside the measured region $x < 0.004$, where the ABJ trajectory has an integrable singularity.

So vanishing of the chirality carried by quarks and the observed large $SU(2)$ asymmetry of the quark sea are the manifestation of the Dirac and flavor structure of fermionic zero modes in the instanton field.

Further, as the mass of a sea quark grows, the nonperturbative part of structure functions dies out faster than the perturbative one because the interaction proceeds through the quark zero modes in the instanton field (parametrically $B_q \propto 1/m_q^2$, m_q

is the constituent quark mass[7]). Then, we may explain the experimentally observed softening of the strange sea[3] as compared to nonstrange one by suppression of the hard nonperturbative sea in Eq. (16a), Eq. (16b). Note, that in ref. [10] these data were explained by the opposite effect, that is by more stronger dependence of the perturbative sea on the quark mass than that of the nonperturbative one, which is extremely surprising.

As for c and b quarks, the nonperturbative interaction is suppressed by the quantities:

$$\epsilon_c \approx (m_u/m_c)^2 \approx (0.30/1.5)^2 \approx 4 \cdot 10^{-2}, \epsilon_b \approx (m_u/m_b)^2 \approx (0.30/4.7)^2 \approx 4 \cdot 10^{-3}. \quad (21)$$

Despite of large suppression ϵ_c of a nonperturbative charm in the proton structure function in the charm production processes already at quite small x due to substantial difference of degrees of $(1-x)$ in Eq. (16a), Eq. (16b), there begin to dominate the hard nonperturbative component, which can be traced from the data of the experiment[23].

At last note that the degrees of the powers for $1/x$ and $(1-x)$ in Eq. (16a), Eq. (16b) refer to asymptotics as $x \to 0$ and $x \to 1$. In the intermediate region, evidently, one should take into account more complicated configurations of the proton wave function.

So, within the model of QCD vacuum as an instanton liquid we obtain the spin-dependent structure functions of sea quarks. It is shown that the EMC data manages the definition of new Regge trajectory connected with ABJ anomaly. The model explains the modern experimental data on the sea quark structure functions.

We think that further experiments on testing the above-mentioned ideas should be done in the following directions: precision measurement of DIS structure functions at small x: measurement of Drell-Yan pair production in polarized $pp-$reactions; measurement of the photon production asymmetry in polarized pp scattering; study of inclusive Λ, Λ_c production in longitudinally polarized pp and pA reactions.

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