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DEFICIENCY OF THE GROSS – LLEWELLYN SMITH SUM RULE AND QCD VACUUM POLARIZATION EFFECT

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From the analysis of the recent CCFR Collaboration data for the structure function $xF_3(x,Q^2)$ ($0.015 < x < 0.65$ and $1.2\ \mathrm{GeV}^2 < |Q^2| < 501\ \mathrm{GeV}^2$) of the deep inelastic neutrino - nucleon scattering we conclude that probably part of the nucleon baryon number is due to the vacuum polarization effects.

The deep inelastic lepton - nucleon scattering processes (DIS) occurring at small distances characterize the internal structure of the elementary particles. In the past few years new experiment data with high precision and in large kinematic region has became available.

Recently the next - to - next - to - leading order QCD analysis of the most precise data for the neutrino - nucleon DIS structure function $xF_3(x,Q^2)$ measured by the CCFR Collaboration at the FERMILAB collider [1] has been performed [2]. This analysis results in the estimation of the Gross - Llewellyn Smith sum rule (GLSsr) [3] in the wide region of squared momentum transfer, Q^2, $2\ \mathrm{GeV}^2 < Q^2 < 500\ \mathrm{GeV}^2$,

$$\mathrm{GLS}(Q^2) = \frac{1}{2}\int_0^1 \frac{xF_3^{\bar{\nu}p+\nu p}(x,Q^2)}{x}dx \tag{1}$$

and reveals at the level of the statistical experimental errors the effect of the deviation [4] from the perturbative QCD prediction:

$$\mathrm{GLS_{QCD}}(Q^2) = 3[1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2(Q^2)) + O(1/Q^2)]. \tag{2}$$

The deficiency, $\Delta\mathrm{GLS} \equiv \mathrm{GLS_{QCD}} - \mathrm{GLS}_{exp}$, at $Q^2 = 10\ \mathrm{GeV}^2$ with four active flavors and the value of QCD parameter $\Lambda^{(4)}_{\overline{MS}} = 213 \pm 31$ MeV is equal to:

$$\Delta\mathrm{GLS}(Q^2 = 10\ \mathrm{GeV}^2) = 0.180 \pm 0.107(stat) \tag{3}$$

and decreases only logariphmically with the squared momentum transfer over all experimental accessible region up to 500 GeV^2. We choose the reference scale at $Q^2 = 10\ \mathrm{GeV}^2$ where the data are most statistical valuable [1] and where the high twist effects and the target mass corrections are negligible [2]. Moreover, it is this scale where large helicity and flavor asymmetries of the proton sea are recently observed in the EMC [5] - SMC [6] and NMC [7] experiments.

In the present letter we suggest the mechanism explaining the possible violation of the GLSsr based on the nonperturbative QCD dynamics. Keeping in mind the

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different experimental and theoretical uncertainties in extracting the value (3) we will consider this number as an upper bound of the effect. The mechanism suggested is highly related to the one violating the Ellis – Jaffe and Gottfried sum rules [8] which characterize the helicity and flavour distributions over nucleon constituents.

In the framework of the parton model the GLSsr for the proton structure function $F_3(x,Q^2)$ corresponds to the conservation of the baryon number, B, [9]

$$\frac{1}{3}\int_0^1 [(u(x,Q^2)-\bar{u}(x,Q^2))+(d(x,Q^2)-\bar{d}(x,Q^2))]\ dx = B(1-\frac{\alpha_s(Q^2)}{\pi}). \tag{4}$$

The baryon charge operator in the quark model is defined by

$$\hat{B}=\frac{1}{6}\int_0^1 (\{u^+(\mathrm{x}),u(\mathrm{x})\}_+ + \{d^+(\mathrm{x}),d(\mathrm{x})\}_+)dx \tag{5}$$

and the baryon number is related to the low – energy spin – averaged matrix element of the isoscalar vector current $J_\mu(\mathrm{x})=\bar{u}\gamma_\mu u+\bar{d}\gamma_\mu d$ over the proton state:

$$<p|J_\mu(0)|p>=12p_\mu B. \tag{6}$$

If the proton state $|p_0>$ contained only free quarks, then the baryon number would be equal one exactly, $B=1$. The index 0 of $|p_0>$ means that a proton (and quarks) is considered over perturbative QCD vacuum with zero contribution of Dirac sea quarks to the baryon number: $<p_0|\hat{B}^{sea}|p_0>=0$.

However, the physical proton is immersed in the strong interacting medium and the phenomena of the confinement and of the spontaneous chiral symmetry breaking occur. As it has been shown by Skyrme and Witten [10, 11] this highly nonlinear QCD vacuum can carry its own baryon number:

$$B^{Skyrme}=\frac{1}{24\pi^2}\epsilon_{0\mu\lambda\rho}\int \mathrm{Tr}\{R_\mu R_\lambda R_\rho\}d\mathrm{x}, \tag{7}$$

where $R_\mu=(\partial_\mu U)U^+$ with $U^+U=1$ is constructed from bosonic fields. It is the effect of the fermion-boson transmutation. In the Skyrme model the chiral soliton baryon charge (7) is fully compensated for by the negative baryon charge induced by sea quarks.

Later Rho, Goldhaber and Brown [12] and Goldstone and Jaffe [13] have suggested that the baryon number (6) of the proton surrounded by the nontrivial (Skyrme) vacuum could be distributed between the normal (canonical) quark contribution, $B^{valence}$, and the part anomalously induced by the vacuum polarization, B^{sea}:

$$B=B^{valence}+B^{sea}. \tag{8}$$

The latter is related to the influence of the regularization procedure on the symmetry properties of the theory and is of pure quantum origin. The classical Skyrme field serves as a tool to define this procedure. Within the chiral bag model for the physical proton state $|p>$ the valence and sea polarization parts of the baryon number are equal to:

$$\begin{aligned}&<p|\hat{B}^{valence}|p>=1,\\ &<p|\hat{B}^{sea}|p>=-B^{Skyrme},\end{aligned} \tag{9}$$

correspondingly. We can write the following sum rule:

$$B^{valence} + B^{sea} + B^{Skyrme} = 1, \tag{10}$$

with $B^{sea} = -B^{Skyrme}$ (by definition) and B^{Skyrme} is invisible in DIS since it characterizes the property of the background vacuum field.

This interpretation of the anomalous sea quark contribution to the baryon charge is in complete analogy with the interpretation of the total angular momentum sum rule for the proton [14]. There, the relative angular momentum inactive in DIS is produced to compensate for the negative helicity of sea quarks created in the field of strong vacuum fluctuation, instanton [8].

In the framework of the chiral bag model [15] when a massless Dirac quark field is confined to a finite region of space by means of a chiral boundary condition parametrized by a chiral angle Θ characterizing a leakage of the baryon charge, the anomalous baryon number of the vacuum is equal to [13]

$$\begin{aligned} B^{Skyrme}(\Theta) &= -\frac{1}{\pi}(\Theta - \frac{1}{2}\sin 2\Theta), && -\frac{\pi}{2} < \Theta < \frac{\pi}{2}, \\ B^{Skyrme}(\Theta + \pi) &= B^{Skyrme}(\Theta), && \text{outside the interval} \quad [-\frac{\pi}{2}, \frac{\pi}{2}]. \end{aligned} \tag{11}$$

This expression is given for the boundary separating the region of intermediate and large distances where soft vacuum effects occur topologically equivalent to a sphere. The chiral boundary condition of general form

$$-i(\hat{n}\vec{\gamma})\ q_L|_S = M(\Theta)\ q_R|_S, \tag{12}$$

where $\hat{n}$ is the outward normal to the surface, is due to specific condition of the confinement of quarks in the closed region. Matrix M is such that the axial vector isotriplet current conservation should be satisfied and simultaneously the flavor singlet axial current should have the anomaly. These requirements fix the form of the chiral boundary condition as an effective surface interaction of the quark fields confined to the hadron with external fields from the vacuum condensate due to instanton exchange [16]:

$$-i\vec{\gamma}\cdot\hat{n}\ q|_s = \exp[i\gamma_5\Theta(\vec{\tau}\cdot\hat{n} + 1)]\ q|_s. \tag{13}$$

As it has been shown in [13] we have the following picture of the baryon charge leakage induced by the background field. The chiral angle Θ varies from zero at very large value of bag radius, $R >> f_\pi^{-1}$ to $-\pi$ as bag radius goes to zero. It corresponds to change of the baryon charge carried by Dirac sea quarks from zero at chiral angle $\Theta = 0$ (large R) to -1 at $\Theta = -\pi$ (small R). When Θ pass $-\pi/2$ the occupied positive quark mode transit sharply into a negative - charge level and the baryon charge of the Dirac sea changes by -1 (11).

Now we can relate the deficiency of the GLSsr (3) with the anomalous vacuum baryon number

$$-\frac{1}{\pi}(\Theta - \frac{1}{2}\sin 2\Theta) = 0.060 \pm 0.036 \tag{14}$$

and then estimate the value of the chiral angle:

$$\Theta = -\frac{\pi}{4}\ \left(0.86\ \begin{matrix} +0.16 \\ -0.23 \end{matrix}\right). \tag{15}$$

The numbers (14) and (15) correspond to an upper bound of the effect.

The origin of the anomaly in the singlet vector current results from the low energy QCD box anomaly: $\omega \to \pi^+\pi^0\pi^-$ [17]. At the same time the isovector chiral flow through the surface controlled by the boundary condition (13) is zero due to the equal number of left - and right - handed chiral quarks. The pseudoscalar isosinglet coupling (13) at the surface has a consequence on the description of the flavor singlet current of the proton (proton spin) [16] and leads to the color anomaly [18].

Finally, the question arises: does the explanation suggested have a particular signal in deep inelastic scattering, e.g. x or Q^2 dependence? The answer is positive [19] because of the structure function $F_3^{\nu p}(x, Q^2)$ defined by vector - axial vector correlator being specific. It's well known [9] that in this channel the Regge singularities have negative $C-$ parity, $C = -1$. They are the $\omega-$ meson exchange with intercept $\alpha_\omega \approx 1/2$ and the Odderon, $C-$ odd partner of the Pomeron, with high intercept $\alpha_O \geq 1$: $F_3(x) = a_\omega x^{-\alpha_\omega} + a_o x^{-\alpha_O}$. The first one is an exchange related to the momentum distribution of valence quarks. The second singularity is due to $C-$ odd vacuum exchange and determines the $x-$ dependence of sea quarks. In the high energy elastic hadron-hadron interactions the cross sections of particle and anti-particle would be different if the Odderon trajectory existed [20]. We hope to clarify the connection between the Dirac sea and Odderon singularity contributions to GLSsr in future publications.

Thus we can interpret the possible violation of the Gross - Llewellyn Smith sum rule observed by CCFR Collaboration in neutrino - nucleon DIS in wide Q^2 interval as a hint at a large polarization effect in the nonperturbative QCD vacuum surrounding the hadron. We also stress that the peculiar interaction of the constituents induced by instantons is also responsible for large helicity and flavor asymmetry of the sea quarks in the proton wave function and the sea quark distribution functions. These and related questions are currently under investigation.

In addition, the experimental investigation (and theoretical understanding) of the behavior of the structure function $F_3(x, Q^2)$ in the region of small x and the calculation of the different QCD corrections at large Q^2 is necessary. The consideration of the nuclear effects is also important to have an unambiguous conclusion about the value of the GLSsr breaking.

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