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SPIN STRUCTURE OF THE NUCLEON AND TRIANGLE ANOMALY

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1. Introduction

Processes with polarized particles draw the increasing attention as the most delicate instrument for verification of the QCD. It is known that QCD allows in principle the description of some spin effects if the spin distribution [1] and quark-gluon correlation functions[2] are known. They cannot be calculated in perturbative QCD just as the usual parton distribution functions and have to be extracted from experiments. An important role play here different sum rules. Among them the Bjorken[3], Ellis-Jaffe[4], Burkhardt-Cottingham[5] sum rules are the most known. A new set of sum rules has been recently proposed in paper [6].

Of particular importance are the sum rules due to conservation laws: the energy-momentum, charge, baryon charge, etc. In this connection it is natural to ask together with R.Feynman: "what restrictions if any on the wave function come from the fact that the total angular momentum of the proton is just 1/2?"

Though Feynman himself did not answer his question, the naive expectation in the spirit of the parton model is

$$\frac{1}{2}\sum_f \Delta q_f + \Delta g = \frac{1}{2}, \tag{1}$$

where Δq_f and Δg are differences of first moments of opposite helicities of quarks (flavour f) and gluons (e.g. $\Delta q_f = \int_0^1 dx \,(q_f^+ - q_f^- + \tilde{q}_f^+ - \tilde{q}_f^-)(x)$). This sum rule however is in contradiction with the leading-log approximation of the QCD evolution equations

$$\begin{pmatrix} \sum_f \Delta \dot{q}_f \\ \Delta \dot{g} \end{pmatrix} = \frac{\alpha_s}{2\pi} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \begin{pmatrix} \sum \Delta q_f \\ \Delta g \end{pmatrix}, \tag{2}$$

where the dot means the derivative with respect to $\log Q^2$. In this approximation $P_{qq} = P_{qg} = 0$ (due to the quark helicity conservation along a quark line) and P_{gq} and P_{gg} are not zero. So, the sum rule (1) cannot be valid for all Q^2.

Several attempts were undertaken to avoid this contradiction:

i) A rather elegant idea was proposed in work[8] to compensate the right-hand side of the second row of (2) due to cancellation of quark and gluon contributions. In this case $\sum \Delta q_f$ and Δg are expressed through the number of flavours.However the picture thus obtained: compensation of two large terms in (1) to obtain 1/2 seems improbable.

ii) There was also an attempt to change the kernels of the evolution equation by adding some terms singular at $x=0$ to guarantee a constant gluon contribution.[9] However, there are no grounds for this procedure[10] (unlike introducing singularity at $x=1$).

iii) A more interesting is the attempt[10,11] to include the orbital angular momentum into sum rule (1) to compensate the growth of the gluon contributinn with increasing Q^2. A more accurate analysis, however, shows that the orbital momentum gives a zeroth contribution to the sum rule.

Really, the commonly adopted receipt for obtaining the sum rule consists in choosing a conserved operator with no anomalous dimention and in calculating it in the limit of free fields. For a quark field such an operator is the axial current which conserves in the chiral limit $m_q \to 0$. For the free field it gives

$$\langle P,S|\sum_f \bar{\psi}_f \gamma^\mu \gamma^5 \psi|P,S\rangle = M S^\mu, \tag{3}$$

where S^μ is the 4-vector of polarisation. The first moment of spin distribution functions is connected just with this matrix element [12] which results in

$$\sum \Delta q_f = 1. \tag{4}$$

The axial current is directly expressed through the canonical tensor of the spin moment of quark[13]

$$S^{\lambda,\mu\nu} = \frac{1}{2}\varepsilon^{\alpha\lambda\mu\nu}\sum_f \bar{\psi}_f \gamma^\alpha \gamma^5 \psi_f \tag{5}$$

and

$$\sum_f \Delta q_f = \langle P,S| S^{\lambda,\mu\nu}|P,S\rangle \, \varepsilon_{\alpha\lambda\mu\nu} S^\alpha. \tag{6}$$

To obtain the conserved angular momentum, one has to add to (6) the orbital momentum

$$\langle P,S|\left(z^\mu T^{\lambda\nu}(z) - z^\nu T^{\lambda\mu}(z)\right)|P,S\rangle \, \varepsilon_{\alpha\lambda\mu\nu} S^\alpha. \tag{7}$$

It is zero however because of the symmetry of matrix elements of the energy-momentum tensor $T^{\mu\nu}$. The same result can be obtained from translation invariance of the matrix element (7), which allows us to put $z=0$. The physical reason of this result is the absence of the natural frame of reference for the inclusive process.

So, without gluons (or with scalar gluons) the quark spin momentum is conserved and again we arrive at the sum rule (4). It was just the way it was obtained several years ago in work [14]. The drawback of this result is neglect of the vector character of gluon fields, which lead, owing to the triangular anomaly, to nonconservation of the axial current. In Sect. 2 we will show that the anomaly changes the relation (1) and makes it consistent with the QCD evolution equations (Sect. 3). The anomaly contribution changes also the Ellis--Jaffe sum rule for the structure function g_1 which gets now in good agreement with experiment.

2. The Gluon Contribution and Axial Anomaly

For the description of the gluon contribution one can use either the expansion in gauge invariant operators [15] or Q^2-dependent parton distributions[16]. These two approaches are consistent with each other with the exception of the first moment:[17] the evolution kernels are known to be different from zero[16], however there is no gauge-invariant operator of the required twist 3 (like the axial current which describes the quark polarisation).

To resolve this contradiction, one may turn to the factorization procedure[18] where the operator product expansion results from the expansion of nonsingular bilocal operators into the Teylor series. A variant of the procedure[19] has been used by us in the transverse polarization analysis[2].

For simplicity let us consider the longitudinal polarization because the sum rule does not depend on the polarization direction due to the well-known equation by Burkhardt-Cottingham[5] or due to rotation invariance on which it is based[1].

Actions similar to [19,2] give

$$\int_{-\infty}^{\infty}\frac{d\lambda}{2\pi} e^{i\lambda x}\begin{bmatrix}\langle \bar{\psi}_\alpha(0)\,\psi_\beta(\lambda n)\rangle_{P,S}\\ \langle A_\rho(0)\,A_\sigma(\lambda n)\rangle_{P,S}\end{bmatrix} = \begin{bmatrix} q(x)\,\hat{P}_{\alpha\beta} + i\xi\,\Delta q(x)\,(\hat{P}\gamma_5)_{\alpha\beta} \\ \frac{g(x)}{x} d_{\rho\sigma} + \xi\,\frac{\Delta g(x)}{x}\varepsilon_{\rho\sigma pn}\end{bmatrix}, \tag{8}$$

where $d_{\rho\sigma} = g_{\rho\sigma} - n_\sigma p_\rho - n_\rho p_\sigma$, $\varepsilon_{\rho\sigma pn} \equiv \varepsilon_{\rho\sigma\alpha\beta} p^\alpha n^\beta$, $(nA)=0$, $p^2 = n^2 = 0$, $pn=1$ and ξ is a polarization value. The parts averaged over spin are written down also for completeness.

Let us notice that the distribution functions obtained have the parton interpretation. It is obvious for quarks, because a density matrix for a free quark has been obtained. For gluons it is easy to see that the right-hand side of (8) is a density matrix of a circular-

-polarized gluon with Stocks parameters $\xi_1 = \xi_2$. The first moments of the spin distribution functions are

$$\Delta q = -\langle \bar\psi \hat n \gamma_5 \psi \rangle_{P,S} \tag{9a}$$

$$\Delta g = \frac{1}{2} \langle A^a_\rho \partial_\mu A^a_\sigma \rangle_{P,S} n^\mu \varepsilon^{\rho\sigma P n}. \tag{9b}$$

Let us stress that in axial gauge the gluon fields can be expressed though the strength tensor $G^{\rho n} \equiv G^{\rho\sigma} n_\sigma$ /20/

$$A_\rho(\lambda n) = \int_0^\infty d\tau\, G_{\rho n}((\lambda + \tau) n). \tag{10}$$

As a result, the moments of the bilocal operator in (8)

$$\langle A_\rho(0) A_\sigma(\lambda n)\rangle_{P,S} = \int_0^\infty dT \int_{-T}^{T} d\tau \langle G_{\rho n}(0) G_{\sigma n}((\lambda+\tau)n)\rangle_{P,S} \tag{11}$$

after integration acquire the form

$$\langle A_\rho(0) (\partial^n)^k A_\sigma(0)\rangle = -\langle G_{\rho n}(0) (\partial^n)^{k-2} G_{\sigma n}(0)\rangle. \tag{12}$$

That is for $k \geq 2$ the local field operators are expressed through the strength operators. (To check (12), it is enough to express in the right-hand-side G through A and use the gauge condition). In the case of interest $k=1$ one integration cannot be accomplished, and we have to deal with nonlocal strength operator matrix element:

$$\langle A_\rho \partial^n A_\sigma \rangle = \int_{-\infty}^{\infty} dT \frac{1}{2} \varepsilon(T) \langle G_{\rho n}(0) G_{\sigma n}(T n)\rangle. \tag{13}$$

That is why we prefer to work with local field operators, the gauge invariance being ensured by transversality of the coefficient function $E^{\rho\sigma}$. Notice also that the local operator in (9b) is proportional to the gluon spin tensor* /13/.

To obtain the relation between the gluon spin operator and similar to (6) one can use the identity /2/

$$\varepsilon^{\rho\sigma P n} n^\mu - \varepsilon^{\rho\mu P n} n^\sigma + \varepsilon^{\sigma\mu P n} n^\rho = \varepsilon^{\rho\sigma\mu n} \tag{14}$$

* We here disregarded the colour structure which can be easily restored. For non-Abelian fields the term $f_{abc} A^a_\rho A^b_\mu A^c_\sigma$ is to be present which gives no contribution due to the gauge condition.

which is a consequence of the space-time being four-dimensional. Using it in (9b) one obtains

$$\Delta g = \frac{1}{2} \langle A_\rho \partial_\mu A_\sigma \rangle \varepsilon^{n\rho\sigma\mu}. \tag{15}$$

Now, one could seemingly use the total angular momentum conservation and determine a relative contribution of quarks and gluons. However, there is the problem that the spin moment is determined in a nonunique way. One can redefine it together with the energy-momentum tensor preserving the equation of motion and the conservation laws. In particular, one can totally absorb the spin moment into the energy-momentum tensor (e.g. the Belinfante tensor /21/) which is naturally symmetric and gives no contribution to the sum rule. So, the relative contribution of gluons in classical field theory seems quite indefinite.

This ambiguity is totally fixed by quantum theory where the conservation of the axial current is broken as is well known by the triangular anomaly of Adler-Bell-Jackiw /22/ (Fig. 1a).

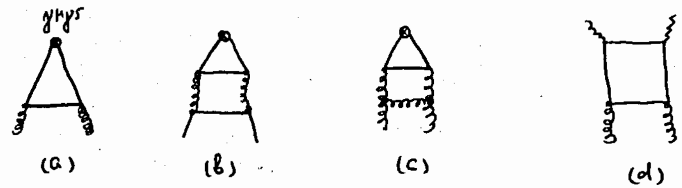

Fig. 1

This anomaly fixes also the conserved quark-gluon current

$$\tilde{j}^\mu_5 = \bar\psi \gamma^\mu \gamma^5 \psi - \frac{g^2}{8\pi^2} \varepsilon^{\mu\sigma\nu\rho} \left(A^a_\sigma \partial_\rho A^a_\nu - \frac{1}{3} f_{abc} A^a_\sigma A^b_\nu A^c_\rho\right). \tag{16}$$

The calculation of the matrix element of the projection of the current on the gauge vector n gives immediately

$$-\langle \tilde{j}^n_5 \rangle_{P,S} = \Delta q + \frac{\alpha_s}{\pi} \Delta g. \tag{17}$$

Due to conservation of the current $\tilde{j}^\mu_5$ the anomalous dimension of the combination is zero in any order of the perturbation theory.

Using the standard method /23/ based on the total angular momentum conservation, $\partial_\mu M^{\mu,\sigma\rho} = 0$ and on the definition of a state vector with helicity ξ

$$\left(\int d^3z\, M^{0,ik}(z)\right) |P,\xi\rangle = \frac{\xi}{2} \varepsilon_{ik\ell} \frac{P_\ell}{m} |P,\xi\rangle$$

one can obtain the sum rule

$$\sum_f \Delta q_f + N_f \frac{\alpha_s}{\pi} \Delta g = 1. \qquad (18)$$

It has been taken into account also that the contribution of the gluon spin is controlled by axial anomaly and that the orbital momentum gives no contribution.

One has to notice that the gluon contribution is linked with the topological number. The difference Δg from zero could mean a nontrivial topological structure of the QCD vacuum. This delicate question, however, needs further investigation. Now it is clear only that the relative contribution of quarks and gluons to sum rule corresponding to the conservation of the angular momentum is determined by such a fundamental feature of the theory as the axial anomaly.

3. Evolution Equations and Sum Rules for the Structure Function

Consider now the evolution of singlet parton distribution functions $\sum \Delta q_f$ and $N_f \alpha_s/\pi \, \Delta g = \Delta \tilde{g}$ with the change of the momentum transfer Q^2. The functions Δq and Δg have the parton interpretation so one can use the results of standard calculations.

The first moment of the evolution kernel $P_{\tilde{g}q}$ can be expressed through the standard kernel P_{gq} obtained in the pioneering work by Allterelly and Parisi [16]

$$P_{\tilde{g}q} = \frac{\alpha_s}{\pi} N_f P_{gq} = \frac{3\alpha_s}{2\pi} N_f C_2(R), \qquad (19)$$

where $C_2(R) = (N^2-1)/2N$, N is the number of colour.

Due to conservation of $\sum_f \Delta q_f + \Delta \tilde{g}$

$$P_{qq} = -P_{\tilde{g}q} \quad \text{and} \quad \gamma_{qq} = -\frac{\alpha_s}{2\pi} \cdot P_{qq} = \left(\frac{g^2}{16\pi^2}\right)^2 12 N_f C_2(R) \qquad (20)$$

which exactly coincides with the results of two-loop calculations (Fig. 1b) of Kadaira [24]. (Recall that one-loop calculations give zero contributions). This serves as a good check of conservation of (18).

For calculation of $P_{\tilde{g}\tilde{g}}$ one has to add to the standard gluon kernel [16] $P_{gg} = \frac{1}{6}(11N - 2N_f)$ the result of differentiation of $\alpha_s(Q^2)$

$$P_{\tilde{g}\tilde{g}} = P_{gg} + \frac{2\pi \beta(\alpha_s)}{\alpha_s^2} \qquad (21)$$

using the expression for $\beta(\alpha_s)$, we get

$$P_{\tilde{g}\tilde{g}} = 0. \qquad (22)$$

Using again the conservation of $\sum_f \Delta q_f + \Delta \tilde{g}$ one can find

$$P_{q\tilde{g}} = -P_{\tilde{g}\tilde{g}} = 0. \qquad (23)$$

This result is a second check of the validity of (19) because, as is well known [23], the anomaly, Fig. 1a, is not renormalized by higher orders of the perturbation theory. So, the diagrams of Fig. 1c have to give zero contribution. Thus, we finally obtain

$$\begin{pmatrix} \sum_f \dot{\Delta q_f} \\ \dot{\Delta \tilde{g}} \end{pmatrix} = \left(\frac{\alpha_s}{2\pi}\right)^2 \begin{pmatrix} -a & 0 \\ a & 0 \end{pmatrix} \begin{pmatrix} \sum \Delta q_f \\ \Delta \tilde{g} \end{pmatrix} \qquad (24)$$

$$a = 3N_f C_2(R) + O(\alpha_s).$$

Notice also that the second eigenvector of (24) is the quark contribution $\sum \Delta q_f$ which is known [4] to be multiplicatively renormalized. This does not prevent, however, its mixing with $\Delta \tilde{g}$ (cf. [25]).

With increasing Q^2 both moments $\sum \Delta q_f$ and $\Delta \tilde{g}$ tend to constant limits

$$\sum_f \Delta q_f(\infty) = \sum_f \Delta q_f(Q_0^2) \exp\left[-\frac{\alpha_s(Q_0^2)}{\pi} \frac{9N_f C_2(R)}{33-2N_f}\right] \qquad (25)$$

$$\Delta \tilde{g}(\infty) = 1 - \sum \Delta q_f(\infty), \qquad (26)$$

the former decreasing and the latter increasing. This change, however, is not large and is about 10% from the region $Q_0^2 \simeq 1$ (GeV/c)^2 where $\alpha_s \simeq 0.2 - 0.3$.

Now let us apply the results obtained to describe deep inelastic scattering on a polarized target. We are interested in the gluon contribution to the first moment of the structure function g_1. As the natural moment of gluon distribution is $\Delta \tilde{g}$, the corresponding coefficient function $\tilde{E}_1$ has to be of order O(1). To find it, we use the result of work [24] where the coefficient function E_1 of the diagram of Fig. 1d has been calculated. For the first moment we have to use only the term independent of $\omega = 1/x$. It is finite and determined by the axial anomaly

$$E_1 = -\frac{g^2}{4\pi^2} N_f \langle e^2 \rangle \quad i.e. \quad \tilde{E}_1 = -\langle e^2 \rangle . \tag{27}$$

So, the first moment of $g_1(x)$ will have the form (see Appendix)

$$g_1 \equiv \int_0^1 dx\, g_1(x) = \frac{1}{2} \sum_f e_f^2 \Delta q_f - \langle e^2 \rangle \Delta \tilde{g} . \tag{28}$$

i.e. the gluon field results in a negative correction to the Ellis-Jaffe sum rule.

For estimation of this correction let us use the sum rule (18) and following Ellis and Jaffe [4,25] neglect the contribution of s-quarks. Then one can express the quark contribution through the constant $g_A \equiv G_A/G_V = 1{,}254 \pm 0{,}006$ and the ratio $F/D = 0{,}631 \pm 0{,}024$

$$\sum_f \Delta q_f \simeq \Delta u + \Delta d = g_A \frac{3F/D - 1}{F/D + 1} = 0{,}687 \pm 0.069 , \tag{29}$$

i.e. the quarks carry about 70% of the nucleon spin at $Q^2 \simeq (1\ \mathrm{GeV}/c)^2$ (the region where g_A and F/D were measured). In its turn the gluon contribution is

$$\Delta \tilde{g} = 1 - \sum_f \Delta q_f = 0.313 \pm 0.069 . \tag{30}$$

Substitution of (30) into (28) gives the possibility of estimating the correction to the Ellis-Jaffe sum rule for the proton. With taking into account s-quarks in the loop of Fig. 1d ($\langle e^2 \rangle = 2/9$) one has

$$g_1^P = \int_0^1 g_1^P(x)\, dx = (0.199 \pm 0.005) - \frac{2}{9}(0{,}313 \pm 0{,}069) = 0.129 \pm 0.009$$

(without s-quarks, $\langle e^2 \rangle = 5/18$, and $g_1^P = 0.112 \pm 0.024$). These values are in good agreement with result of the EMC-group [26] $g_1^P = 0{,}113 \pm 0.012 \pm 0.025$ at $Q^2 \simeq 10\ (\mathrm{FeV}/c)^2$. For the neutron we predict $g_1^n \simeq -0.08$.

4. Conclusion and Discussion

Thus, we have shown that the contribution of the spin of gluons to the spin of the nucleon is determined by the axial anomaly of Adler-Bell-Jackiw. The new sum rule corresponding to conservation of the angular momentum is consistent with the QCD evolution equations in all orders of α_S. The axial anomaly gluon contribution gives also a negative correction to the Ellis-Jaffe sum rule for which compensates the discrepancy with experiment.

The usually made assumption that $\Delta S \simeq 0$ allows us to estimate the contribution of $\sum \Delta q_f$ and $\Delta \tilde{g}$ from the low-energy β-decay

physics ($Q^2 \simeq 1\ \mathrm{GeV}^2$) and find that gluons carry about 30% of the nucleon spin and reduce the Ellis-Jaffe result almost to the experimental value. This also removes the contradiction of the EMC result with the Bjorken sum rule. A serious question is high-twist corrections to the deep inelastic scattering. However large enough $\langle Q^2 \rangle$ for the EMC data and also the calculations of g_1 by the QCD sum rule method [27] indicate that these corrections do not possibly exceed 30%. The role of higher-twist corrections could become clear from experiments at higher Q^2.

Recently it has been suggested [28,29] that the naive parton model assumption $\Delta S \simeq 0$ is not valid and that the Skyrme model combined with the $1/N_c$ expansion results in $\sum \Delta q_f = 0$ [28]. If so, then the EMC result is an argument against the Skyrme model because together with the Bjorken relation and SU(3) flavour hyperon decay $\frac{1}{\sqrt{3}}(\Delta u + \Delta d - 2\Delta S) = 0{,}39$ explain the measured value of g_1^P without gluon contribution. However, the gluon contribution being large in this case ($\Delta \tilde{g} \simeq 1$ due to (18)) ruins this agreement.

The proposed gluon contribution can be directly measured in many hard processes with polarized particles. Part of them is listed in [28]. The most important in our opinion are J/ψ and charm production in deep inelastic scattering [29] and in Drell-Yan processes.

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Appendix

Due to an important role of the gluon contribution to the Ellis-Jaffe sum rule, let us consider its derivation to a greater detail. We start with the factorized expression for virtual photon forward scattering amplitude

$$T^{\mu\nu} = \Delta q \otimes \frac{1}{4} Sp\left(\hat{p} \gamma^5 \hat{t}_q^{\mu\nu}\right) + \Delta g \otimes \left(i \varepsilon_{\rho\sigma p n} \frac{t_g^{\rho\sigma\mu\nu}}{x}\right) . \tag{A.1}$$

where $\otimes$ means a convolution in x, and t_q and t_g are quark and gluon Green functions calculated in [24,30]. The summation over quark flavours with the process-dependent weight is implied, as usual

$$t_q^{\mu\nu}(p,q) = \langle 0 | T(\bar{\psi}(-p) j^\mu(-q) j^\nu(q) \psi(p)) | 0 \rangle_{tr} = \varepsilon^{\mu\nu q \sigma} \gamma^\sigma \gamma^5 \frac{1}{(pq)} \sum_{n=1,3,\dots} \omega^n$$

$$t_g^{\rho\sigma\mu\nu}(p,q) = \langle 0|T(A_\rho(-p)J^\mu(q)J^\nu(q)A_\sigma(p))|0\rangle_{tr} = i\,\varepsilon^{\mu\nu q\alpha}\varepsilon_{\rho\sigma\alpha p}\frac{1}{Q^2}\frac{g^2}{2\pi}N_f + O(\omega)$$

Only the terms leading in α_s are taken into account. Changing $p \to xp$ and taking into account only the zero-order term in x/x_{Bj} in t_q and t_g (for gluons it is determined by the axial anomaly) one obtains for the first moment

$$T_1^{\mu\nu} = -\sum_f \Delta q_f \varepsilon^{\mu\nu qp}\frac{2}{Q^2} + \Delta g\,\varepsilon^{\mu\nu qp}\frac{g^2}{\pi^2}N_f = -\frac{2\varepsilon^{\mu\nu pq}}{Q^2}\left(\sum\Delta q - 2\Delta\tilde{g}\right).$$

One should notice also that the convolution of the total expression for the gluon Green function [24] with $\varepsilon^{\rho\sigma p n}$ enables us to obtain the coefficient function $E_{1,n}$ for other moments. The result differs from that of [24] by factor 4 that may be a consequence of normalization[31] of the amputated Green functions of local singlet operators.

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