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The Quark Contribution to the Nucleon Spin from Polarized Lepton-Nucleon DIS with Neutral Current

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The expressions for the contributions (u, d, s) quark flavours and valence quarks to nucleon spin in terms the first moments of spin-dependent electroweak structure functions DIS polarized leptons off polarized protons and deuterons through neutral current were obtained. Their numerical evaluations are presented for COMPASS deuteron data.

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Understanding the spin structure of the nucleon is a fundamental goal in hadronic physics [1, 2]. The polarized deep inelastic scattering (DIS) have provided important insights into the spin structure of the nucleon. Precise DIS experiments have found that the spin of the quarks and antiquarks $(\Delta\Sigma)$ account for only $\sim 30\%$ of the spin of the nucleon. The remainder will to give the contributions from the gluon spin (Δg) and the orbital angular moments of the quarks (L_q) and of the gluons (L_g).

The RHIC is a unique tool for exploring gluon polarization through collisions of polarized proton beams [3–5]. The recent RHIC results shows, for the first time, a positive gluon polarization in the region $x > 0{,}05$. At lower values x the gluon helicity distribution is stile poorly constrained. The proposed electron-ion collider (EIC)[6, 7] offers new opportunities to study the spin structure of the nucleon due to polarized electron and hadron beams, high luminosity, high center of mass energy. At the proposed EIC where momentum transfers Q^2 is large necessary to take into consideration the contribution of the weak interaction to a measurable quantities [8].

The processes DIS polarized leptons off polarized nucleons with the neutral current

$$\vec{l} + \vec{N} \xrightarrow{\gamma, Z} l + X \tag{1}$$

play important role in the study of the spin structure nucleon. In the experiments EMC, SMC, E142,...E155, HERMES, COMPASS, JLab were obtained the data, which formulated the modern performance about the contribution spin the quarks and the gluons in the nucleon.

The further progress will be in the experiments on the EIC [6, 7]. Here the kinematic range could be further extended down to $x \sim 10^{-4}$.

The EIC would expand the opportunities for high-energy scattering on polarized light nuclei (D, ^3He, ...) and measurements of neutron structure. The EIC would allow extract neutron structure function with unprecedented precision.

The interaction in the processes (1) will to realize as a counter polarized beams by very large value Q^2. Therefore the calculation is of weak interaction (exchange Z-bozon)

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necessary since its contribution in measurable quantities can be compare with the electromagnetic interaction.

The structure function of deuteron is

$$g_1^d = \frac{1}{2}(g_1^p + g_1^n)(1 - \frac{3}{2}\omega)$$

where $\omega = 0.05 \pm 0{,}01$ is the probability D-state in the wave function of deuteron.

Therefore structure function of neutron g_1^n can to extract from structure deuteron. The structure function of neutron g^n can be obtained from the measurements on polarized ^3He target.

$$g_1^{^3He} \sim P_n g_1^n + 2P_p g_1^p,$$

where effective polarization of neutron and proton $P_n = 0{,}86 \pm 0{,}02$ and $P_p = -0{,}028 \pm 0{,}004$, i.e. polarized ^3He acts effectively how polarized neutron target.

In electroweak processes (1) have to be two independent structure functions g_1 and g_6. For the analysis of the spin structure nucleon will to applicate the first moments these structure function:

$$\Gamma_{1,6}(Q^2) = \int_0^1 g_{1,6}(x, Q^2)dx.$$

For DIS with the neutral current (1) the first moments $\Gamma_{1,6}$ of proton are [9]:

$$\Gamma_1^p(Q^2) = a_u(Q^2)\Big[\Delta u(Q^2) + \Delta\overline{u}(Q^2)\Big] + \\ + a_d(Q^2)\Big[\Delta d(Q^2) + \Delta\overline{d}(Q^2)\Big] + a_s(Q^2)\Big[\Delta s(Q^2) + \Delta\overline{s}(Q^2)\Big]. \tag{2}$$

$$\Gamma_6^p(Q^2) = b_u(Q^2)\Delta u_V(Q^2) + b_d(Q^2)\Delta d_V(Q^2). \tag{3}$$

where $\Delta q_V(Q^2) = \Delta q(Q^2) - \Delta\overline{q}(Q^2)$.

In the expressions (2) and (3):

$$a_u = \frac{2}{9} + \frac{2}{3}\eta_{\gamma,Z} g_{V,u} + \frac{1}{2}\left(g_V^2 + g_A^2\right)_u, \quad a_{d,s} = \frac{1}{18} - \frac{1}{3}\eta_{\gamma,Z} g_{V(d,s)} + \frac{1}{2}\eta_Z\left(g_V^2 + g_A^2\right)_{d,s},$$

$$b_u = \frac{2}{3}\eta_{\gamma,Z} g_{A,u} + \eta_Z\Big(g_V g_A\Big)_u, \quad b_d = -\frac{1}{3}\eta_{\gamma,Z} g_{A,d} + \eta_Z\Big(g_V g_A\Big)_d,$$

$$g_{V,u} = \frac{1}{2} - \frac{4}{3}\sin^2\Theta_W, \quad g_{A,u} = \frac{1}{2}, \quad g_{V(d,s)} = -\frac{1}{2} + \frac{2}{3}\sin^2\Theta_W, \quad g_{A(d,s)} = -\frac{1}{2}.$$

$\eta_{\gamma,Z} = \frac{G m_Z^2 (g_V + g_A)}{2\sqrt{2}\pi\alpha}\frac{Q^2}{Q^2+m_Z^2}$, $\eta_Z = \eta_{\gamma,Z}^2$, $G-$ Fermi constant, m_Z- mass bozon;
$g_V = \frac{1}{2} + 2\sin^2\Theta_W$, $g_A = -\frac{1}{2}$.

The first moments $\Gamma^n_{1,6}$ of neutron obtain respectively

$$\Gamma_1^n = a_d(\Delta u + \Delta\bar{u}) + a_u(\Delta d + \Delta\bar{d}) + a_s(\Delta s + \Delta\bar{s}), \tag{4}$$

$$\Gamma_6^n = b_d\Delta u_V + b_u\Delta d_V. \tag{5}$$

The first moments of proton and neutron (4) can to perform in the form

$$\Gamma_1^{p,n} = \frac{1}{3}(a_u + a_d + a_s)a_0 \pm \frac{1}{2}(a_u - a_d)a_3 + \frac{1}{6}(a_u + a_d - 2a_s)a_8, \tag{6}$$

where $a_0 \overset{\overline{MS}}{=} \Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$ is the total contribution of the quark and the antiquark in the nucleon spin;

$$a_3 = (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d}), \tag{7}$$

$$a_8 = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s}). \tag{8}$$

The measurements of the first moments Γ_1^p, Γ_1^n allow to determine from (6) in leading order QCD $a_0 = \Delta\Sigma$ with known measurable quantities a_3 and a_8.

In any order at $\alpha_s(Q^2)$ in $\overline{MS}-$ scheme (6) receive the form (see also [10, 11])

$$\begin{aligned}\Gamma_1^{p,n} = \frac{1}{3}(a_u + a_d + a_s)a_0\, \Delta C_s(\alpha_s) \pm \frac{1}{2}(a_u - a_d)a_3\, \Delta C_{Ns}(\alpha_s) + \\ + \frac{1}{6}(a_u + a_d - 2a_s)a_8\, \Delta C_{Ns}(\alpha_s)\end{aligned} \tag{9}$$

where $\Delta C_s(\alpha_s)$, $\Delta C_{Ns}(\alpha_s)$ are Wilson coefficients [2].

The determination of the contributions in the nucleon spin each the quark flavour $(\Delta u + \Delta\bar{u})$, $(\Delta d + \Delta\bar{d})$, $(\Delta s + \Delta\bar{s})$ is realized from (2) (or (4) for neutron), (7), (8).

For $N = p$ are

$$\begin{aligned}\Delta u + \Delta\bar{u} &= \frac{2(\Gamma_1^p + a_3 a_d) + a_s(a_8 + a_3)}{2(a_u + a_d + a_s)}\\ \Delta d + \Delta\bar{d} &= \frac{2(\Gamma_1^p - a_3 a_u) + a_s(a_8 - a_3)}{2(a_u + a_d + a_s)}\\ \Delta s + \Delta\bar{s} &= \frac{2(\Gamma_1^p - a_3 a_u) - (a_u + a_d)(a_8 - a_3)}{2(a_u + a_d + a_s)}\end{aligned} \tag{10}$$

The results for the scattering on the polarized neutron are obtained from (10) by $a_n \leftrightarrow a_d$.

The first moments of the deuteron are

$$\Gamma_{1,6}^d = \frac{\Gamma_{1,6}^p + \Gamma_{1,6}^n}{2}(1 - 1.5\omega). \tag{11}$$

From (9) and (11) we obtain

$$\Gamma_1^d = (1 - 1.5\omega)\frac{1}{6}\Big[2(a_u + a_d + a_s)a_0\, \Delta C_s + (a_u + a_d - 2a_s)a_8\, \Delta C_{Ns}\Big].$$

Hence,

$$a_0 = \frac{1}{2(a_u + a_d + a_s)\Delta C_s}\left[\frac{6\Gamma_1^d}{1 - 1.5\omega} - (a_u + a_d - 2a_s)a_8\, \Delta C_{Ns}\right] \tag{12}$$

The first moment of deuteron Γ_1^d is expressed through the quark flavours with help (2), (4):

$$\frac{2\Gamma_1^d}{1-1.5\omega} = (a_u + a_d)(\Delta u + \Delta\bar{u}) + (a_u + a_d)(\Delta d + \bar{d}) + 2a_s(\Delta s + \Delta\bar{s}). \tag{13}$$

Applying (13), (7) and (8) we obtain the contributions of quark flavours in the nucleon spin

$$\begin{aligned}
\Delta u + \Delta\bar{u} &= \frac{\frac{2\Gamma_1^d}{1-1.5\omega} + a_8 a_s + a_3(a_u + a_d + a_s)}{2(a_u + a_d + a_s)} \\
\Delta d + \Delta\bar{d} &= \frac{\frac{2\Gamma_1^d}{1-1.5\omega} + a_8 a_s - a_3(a_u + a_d + a_s)}{2(a_u + a_d + a_s)} \\
\Delta s + \Delta\bar{s} &= \frac{\frac{2\Gamma_1^d}{1-1.5\omega} - a_8(a_u + a_d)}{2(a_u + a_d + a_s)}
\end{aligned} \tag{14}$$

The first moment Γ_6^d expresses the total contribution of the valence quarks $\Delta u_V + \Delta d_V = \frac{2\Gamma_6^d}{1-1.5\omega}$ without the complementary quantities a_3 and a_8.

In Table 1 give the numerical evaluations of the quark contributions obtained through (12), (14) with $\Gamma_1^N = \frac{\Gamma_1^d}{1-1.5\omega}$ measured COMPASS [12] in comparison with only $\gamma-$exchange, data HERA [11] and the results of QCD-analysis [2].

Table 1: The quark contribution with $Z-$exchange in processes (1)

	(γ, Z) exchange central value	γ exchange central value	HERA [11] NNLO central value	QCD analysis [2] NLO central value
$a_0 \overset{\overline{MS}}{=} \Delta\Sigma$	0.28	0.30	0.33	0.30
$\Delta u + \Delta\bar{u}$	0.825	0.832	0.842	0.834
$\Delta d + \Delta\bar{d}$	−0.444	−0.437	−0.427	−0.436
$\Delta s + \Delta\bar{s}$	−0.102	−0.095	−0.085	−0.094

From the Table 1 can to see, that a_0 and $(\Delta s + \Delta\bar{s})$ with the calculation of the weak interaction are distinguished from the data HERA ($\gamma-$exchange) on 18% and 20%, but $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$ – on 2% and 4% respectively. The comparison with $\gamma-$exchange and QCD-analysis [2] shows the difference a_0, $(\Delta s + \Delta\bar{s})$ for the electroweak interaction order 7%; $(\Delta u + \Delta\bar{u})$, $(\Delta d + \Delta\bar{d})$ is not more 1,5%.

Thus, were obtained the expressions for the contributions quark flavours $(\Delta u + \Delta\bar{u})$, $(\Delta d + \Delta\bar{d})$, $(\Delta s + \Delta\bar{s})$ and valence quarks $(\Delta u_V + \Delta d_V)$ in the nucleon spin in inclusive DIS of polarized leptons on polarized protons, neutrons, deuterons with the neutral current through the first moments polarized electroweak SF. The measurements these first moments can to realize in the experiments on EIC.

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