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# HIGHER TWIST EFFECTS IN DIS: AN OUTLINE OF DIQUARK CONTRIBUTIONS*

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## Abstract

A quark–diquark picture of the nucleon, previously introduced in the description of several exclusive and inclusive processes at intermediate $Q^2$ values, is found to accurately model the higher-twist data on the unpolarized proton structure function $F_2^p(x, Q^2)$. The main results of the model are summarized. The emerging set of parameters is consistent with the diquark properties suggested by other experimental and theoretical analyses. Higher-twist corrections to the Bjorken and Gottfried sum rule are also estimated in the framework of the same quark-diquark model. The resulting corrections to both sum rules turn out to be negligible.

**Key-words:** Deep inelastic scattering; Higher twist; Diquark.

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# 1 Introduction

Recent data from Deep Inelastic Scattering (DIS) experiments at CERN and SLAC have provided precise information on the unpolarized proton structure function $F_2^p(x, Q^2)$ and have allowed a quantitative estimate of higher-twist terms [1, 2].

Higher-twist contributions to DIS are expected to originate from quark and gluon correlations, and we assume here that they can be described by a quark–diquark picture of the nucleon. Diquarks originate from QCD colour forces and model correlations between two quarks inside the nucleon which, at moderate $Q^2$ values, interact collectively and behave as bound states.

The diquark model is supported by a number of phenomenological successes in the description of many physical phenomena, such as: the behaviour of the DIS structure functions at Bjorken $x \to 1$, the inclusive large $p_T$ production of deuterons, protons and other baryons in $pp$ interactions, several exclusive processes and decays [3, 4]. There is little doubt that two quark correlations are present inside nucleons and that they might play a significant rôle in processes at moderate $Q^2$ values, precisely the region where the higher-twist effects have been observed [$Q^2$ up to $\simeq 10 - 20$ (GeV/$c$)$^2$].

# 2 Diquark contributions to F$_2$

The diquark contributions to DIS have been studied in several papers [5, 6], mainly taking into account only spin 0, scalar diquarks, in simplified versions of the quark-diquark model of the nucleon. A most general calculation of spin 0 and spin 1 diquark contributions to DIS was performed in Ref. [7], allowing for a vector diquark anomalous magnetic moment and for scalar–vector and vector–scalar diquark transitions; however, at that time, no attempt was made of fitting the experimental data due to the lack of detailed information on the higher-twist contributions alone. This was performed more recently [8].

Let us assume the nucleon to be a quark–diquark state where the diquark mimics the correlations between two quarks which, at moderate momentum transfer, interact collectively and behave as a bound state. When probing the nucleon with the virtual photon in DIS we have then three kinds of contributions: the scattering off the single quark, the elastic scattering off the diquark, and the inelastic diquark contribution, that is the scattering off one of the quarks inside the diquark. Eventually, at large enough $Q^2$ values, the elastic diquark contribution, weighted by form factors, vanishes and one recovers the usual pure quark results.

The expression of the structure functions $F$, in the quark-diquark parton model, is then given in general by:

$$
\begin{aligned}
F(x, Q^2) &= \sum_q F^{(q)} + \sum_S F^{(S)} + \sum_V F^{(V)} \\
&+ \sum_{q_S} F^{(q_S)} + \sum_{q_V} F^{(q_V)} + \sum_{S,V} F^{(S-V)} + \sum_{S,V} F^{(V-S)} ,
\end{aligned} \tag{1}
$$

where $(q)$ denotes the single quark contribution, $(S)$ and $(V)$ respectively the scalar and vector diquark ones, and $(q_S)$ [$(q_V)$] the contribution of the quark inside the scalar [vector] diquark. We have also allowed for elastic diquark contributions with a scalar–vector $(S-V)$ or vector–scalar $(V-S)$ transition.

Let us consider here the unpolarized structure function $F_2(x,Q^2)$ only. It is straightforward to extract from the full contribution of the quark–diquark model to $F_2$ all terms which are proportional to the diquark form factors [8]. These terms vanish at large $Q^2$ values, but at moderate $Q^2$ values they give non negligible contributions. These are the terms which we assume to model higher-twist effects in DIS. Explicitely – following the notations of Refs. [7,8] – they are given by

$$\begin{aligned} F_2^{HT} &= \sum_S e_S^2\, S(x)\, x\, D_S^2 + \sum_V \frac{1}{3} e_V^2 V(x)\, x \Big\{ \Big[ \Big(1+\frac{Q^2}{2m_N^2 x^2}\Big) D_1 + \\ &- \frac{Q^2}{2m_N^2 x^2} D_2 + Q^2\Big(1+\frac{Q^2}{4m_N^2x^2}\Big) D_3 \Big]^2 + 2\Big[D_1^2 + \frac{Q^2}{4m_N^2x^2} D_2^2\Big]\Big\} \\ &+ \frac{1}{4}\sum_S e_S^2\, S(x)\, xQ^2\, D_T^2 + \frac{1}{12}\sum_V e_S^2\, V(x)\, xQ^2\, D_T^2 \\ &- \sum_{q_S} e_{q_S}^2\, x\, q_S(x,Q^2) D_S^2 - \sum_{q_V} e_{q_V}^2\, x\, q_V(x,Q^2) D_V^2 \,. \end{aligned} \tag{2}$$

Notice that, depending on the actual behaviour of the form factors, one not only obtains contributions proportional to $1/Q^2$, but also to higher powers of $1/Q^2$, which might be significant in the lowest $Q^2$ range of the experimental data [1, 2]. Notice also that Eq. (2) has both positive and negative contributions, so that it might yield positive or negative higher-twist values, according to the different $x$ or $Q^2$ ranges.

The valence quark content of the proton in the quark-diquark model [9] is given by the flavour and spin wave function:

$$\begin{aligned} |p, S_z = \pm 1/2\rangle &= \pm\frac{1}{3}\Big\{ \sin\Omega [\sqrt{2} V_{(ud)}^{\pm 1} u^{\mp} - 2 V_{(uu)}^{\pm 1} d^{\mp} \\ &+ \sqrt{2} V_{(uu)}^0 d^{\pm} - V_{(ud)}^0 u^{\pm}] \mp 3\cos\Omega\, S_{(ud)} u^{\pm} \Big\} \,, \end{aligned} \tag{3}$$

where $V_{(ud)}^{\pm 1}$ stands for a $(ud)$ vector diquark with the third component of the spin $S_z = \pm 1$, $u^{\mp}$ is a $u$ quark with $S_z = \mp 1/2$ and so on. The vector and scalar diquark components have different weights, so that the probabilities of finding a vector or scalar diquark in the proton are $\sin^2\Omega$ and $\cos^2\Omega$ respectively. From Eqs. (2, 3) and following the notation of Ref. [8] we finally get, for a proton

$$\begin{aligned} (F_2^{HT})_p &= \frac{1}{9}\cos^2\Omega\, \Big[ f_S(x) - [4 f_{u_S}(x,Q^2) + f_{d_S}(x,Q^2)] \Big]\, x\, D_S^2 \\ &+ \frac{1}{81}\sin^2\Omega\, [f_{V_{(ud)}}(x) + 32 f_{V_{(uu)}}(x)]\, x \Big\{ \Big[ \Big(1+\frac{Q^2}{2m_N^2x^2}\Big) D_1 \\ &- \frac{Q^2}{2m_N^2x^2} D_2 + Q^2\Big(1+\frac{Q^2}{4m_N^2x^2}\Big) D_3\Big]^2 + 2\Big[D_1^2 + \frac{Q^2}{4m_N^2x^2} D_2^2\Big]\Big\} \\ &- \frac{1}{27}\sin^2\Omega\, [16 f_{u_{V_{(uu)}}}(x,Q^2) + 5 f_{u_{V_{(ud)}}}(x,Q^2)]\, x\, D_V^2 \\ &+ \frac{1}{36}\Big[\cos^2\Omega\, f_S(x) + \frac{1}{9}\sin^2\Omega\, f_{V_{(ud)}}(x)\Big]\, xQ^2\, D_T^2 \,. \end{aligned} \tag{4}$$

We have adopted the following parametrization of the different distribution functions:

$$P(x) = \langle P\rangle\, f_P(x) = \langle P\rangle\, N_P\, x^{\alpha_P}(1-x)^{\beta_P} \tag{5}$$

for each kind of parton $P = S, V, q_S, q_V$; the $N_P$'s are the proper normalization constants [8] such that $\int_0^1 dx\; f_P(x) = 1$; $\langle P\rangle$ gives the average number of valence partons $P$ inside the proton according to Eq. (3).

Concerning the diquark form factors we have chosen the most simple expressions which agree both with the asymptotic perturbative QCD predictions [10] and the pointlike, $Q^2 \to 0$, limits:

$$\begin{aligned}
D_S &= \frac{Q_S^2}{Q_S^2+Q^2}\\
D_1 &= \left(\frac{Q_V^2}{Q_V^2+Q^2}\right)^2\\
D_2 &= (1+\kappa)D_1\\
D_3 &= \frac{Q^2}{m_N^4}D_1^2\\
D_V &= D_1\\
D_T &= \frac{\sqrt{Q^2}}{m_N}D_1
\end{aligned} \tag{6}$$

where $\kappa$ is the vector diquark anomalous magnetic moment.

We have then used Eq. (4), with the parametrizations given in Eqs. (5) and (6), as a model to fit the experimental data on the higher-twist contributions to $F_2^p$. [1, 11]. We have neglected the small effect due to the perturbative QCD $Q^2$ evolution of the single quark distribution functions $f_{u_S}$, $f_{d_S}$, $f_{u_{V(ud)}}$ and $f_{u_{V(uu)}}$.

The results of our best fits are indeed very good and are given in Ref. [8].

The corresponding values of the free parameters turn out to be:

$$\begin{gathered}
\cos^2\Omega = 0.81 \qquad Q_S^2 = 2.02\ (\mathrm{GeV}/c)^2 \qquad Q_V^2 = 1.21\ (\mathrm{GeV}/c)^2\\
\alpha_S = 2.13 \qquad \beta_S = 18.51 \qquad \alpha_V = 7.93 \qquad \beta_V = 3.32\\
\beta_{u_S} = 5.13 \qquad \beta_{d_S} = 5.13 \qquad \beta_{u_{V(ud)}} = 8.41 \qquad \beta_{u_{V(uu)}} = 8.41
\end{gathered} \tag{7}$$

The values of $\alpha_{u_S}$, $\alpha_{d_S}$, $\alpha_{u_{V(ud)}}$ and $\alpha_{u_{V(uu)}}$ have been fixed to be $-0.5$ in agreement with the expected small $x$ behaviour of the valence quark distributions. The value of $\kappa$ which allows the best fits is $\kappa = 0$.

It is important to stress that the diquark features, as emerging from the values of the best fit parameters, Eqs. (7), are consistent with the expectations from many other studies and applications of quark-diquark models of the nucleon [3]. Scalar diquarks turn out to be more abundant ($\cos^2\Omega = 0.81$) and more pointlike ($Q_S^2 > Q_V^2$) than vector ones. Also, the average momentum fraction, $x$, carried by a scalar diquark, proportional to its average mass, is smaller, as expected, than the average $x$ of a vector diquark.

The deep inelastic scattering of neutrinos on unpolarized nucleons has also been considered in the framework of the same (and most general) quark–diquark model [12]. The resulting scaling violations have been discussed, but a detailed study of the higher-twist terms and their possible evaluation are at present impossible, due to lack of experimental data.

## 3 Diquark contribution to Bjorken sum rule

Several recent measurements of the polarized structure functions $g_1^p(x)$ and $g_1^n(x)$ both for protons and neutrons [13] have allowed the first tests of the fundamental Bjorken sum rule: [14]

$$\int_0^1 dx\ [g_1^p(x) - g_1^n(x)] = S_{Bj} = \frac{a_3}{6} E_{NS}(Q^2)\,, \tag{8}$$

where $a_3 = 1.2573 \pm 0.0028$ is the neutron $\beta$-decay axial coupling. The above equation holds on ground of isospin invariance, at leading twist in the Operator Product Expansion; the coefficient function $E_{NS}$ has been computed up to third order [15] in the strong coupling constant $\alpha_s$:

$$E_{NS}(Q^2) = 1 - \frac{\alpha_s}{\pi} - 3.58\left(\frac{\alpha_s}{\pi}\right)^2 - 20.22\left(\frac{\alpha_s}{\pi}\right)^3\,, \tag{9}$$

where a number of three active flavours is assumed.

Data are available at $Q^2 = 2$ and 4.6 $(\mathrm{GeV}/c)^2$: at such values of $Q^2$ a comparison of Bjorken sum rule with experiment should also take into account possible higher-twist or target mass corrections, not included in Eq. (8):

$$\int_0^1 dx\ [g_1^p(x) - g_1^n(x)] = S_{Bj}(Q^2) + \delta S_{HT}^{Bj} + \delta S_T^{Bj}\,. \tag{10}$$

Some evaluations of target mass [16–18] and higher-twist corrections can be found in the literature [13], either in the framework of the Drell-Hearn-Gerasimov sum rule [19] or of the QCD sum rules [16, 20]. Some of these corrections may be sizeable at $Q^2 \simeq 2$ $(\mathrm{GeV/c})^2$, but the final comparison with data shows no significant violation of the Bjorken sum rule. Let us notice that reliable estimates of the higher-twist contributions are of fundamental importance in view of the attempts to exploit the Bjorken sum rule (8) in order to extract the value of the strong coupling constant $\alpha_s$.

It is then natural to evaluate the higher-twist corrections to $S_{Bj}$ in the framework of the quark-diquark model of the nucleon [21]. We would like to stress that the diquark approach, being a physically motivated and self consistent model, rather than an expansion in powers of $1/Q^2$, has the unique feature of taking into account a full set of higher-twist corrections and not only the leading ones. Confident in its physical content, we have adopted the same diquark model, with the same parameters, as given in Eq. (7): therefore the results presented here are parameter free predictions.

The elastic diquark contributions have been studied in Ref. [7] and, for the polarized structure function $g_1(x, Q^2)$, they read

$$g_1^{(V)}(x, Q^2) = \frac{1}{4} e_V^2\, \Delta V \left[\left(2 + \frac{Q^2}{2m_N^2 x^2}\right)\left(D_1 D_2 + \frac{1}{2} Q^2 D_2 D_3\right) - \frac{Q^2}{4m_N^2 x^2} D_2^2\right] \tag{11}$$

where $\Delta V$ denotes the difference between the number density of vector diquarks with spin parallel and antiparallel to the nucleon spin.

Following the notations of Ref. [7] the higher-twist diquark contributions to $g_1$ for protons and neutrons are given by:

$$\begin{aligned} \left[g_1^{HT}\right]_p &= \frac{1}{4}\left(\frac{16}{9}\Delta V_{uu} + \frac{1}{9}\Delta V_{ud}\right)\left[\left(2 + \frac{Q^2}{2m_N^2x^2}\right)\left(D_1D_2 + \frac{1}{2}Q^2D_2D_3\right)\right. \\ &- \left.\frac{Q^2}{4m_N^2x^2}D_2^2\right] - \frac{1}{2}\left(\frac{4}{9}\Delta u_{_{V_{uu}}} + \frac{4}{9}\Delta u_{_{V_{ud}}} + \frac{1}{9}\Delta d_{_{V_{ud}}}\right)D_V^2\,, \end{aligned} \tag{12}$$

$$\begin{aligned} \left[g_1^{HT}\right]_n &= \frac{1}{4}\left(\frac{1}{9}\Delta V_{uu} + \frac{1}{9}\Delta V_{ud}\right)\left[\left(2 + \frac{Q^2}{2m_N^2x^2}\right)\left(D_1D_2 + \frac{1}{2}Q^2D_2D_3\right)\right. \\ &- \left.\frac{Q^2}{4m_N^2x^2}D_2^2\right] - \frac{1}{2}\left(\frac{1}{9}\Delta u_{_{V_{uu}}} + \frac{4}{9}\Delta u_{_{V_{ud}}} + \frac{1}{9}\Delta d_{_{V_{ud}}}\right)D_V^2\,. \end{aligned} \tag{13}$$

The negative contributions come from the scattering off the quarks inside the diquarks, weighted by a factor $(1 - D_V^2)$, with $D_V$ given in Eqs. (6, 7). In Eq. (13) we have already used isospin relationships and all distribution functions refer to the proton; $\Delta q$ is the usual helicity density carried by quark $q$ and the suffices refer to the type of diquark it comes from.

Subtracting Eq. (13) from (12) yields

$$\begin{aligned} \left[g_1^{HT}\right]_{p-n} &= \frac{1}{3}\Delta V_{uu}\left[\left(2 + \frac{Q^2}{2m_N^2x^2}\right)\left(D_1D_2 + \frac{1}{2}Q^2D_2D_3\right) - \frac{Q^2}{4m_N^2x^2}D_2^2\right] \\ &- \frac{1}{6}\Delta u_{_{V_{uu}}}D_V^2\,, \end{aligned} \tag{14}$$

where, according to Eq. (3),

$$\begin{aligned} \Delta V_{uu}(x) &= \frac{4}{9}\sin^2\Omega\ f_{V_{uu}}(x) \\ \Delta u_{_{V_{uu}}}(x) &= \frac{8}{9}\sin^2\Omega\ f_{u_{V_{uu}}}(x) \end{aligned} \tag{15}$$

and the $f_P$ distributions are the same as defined in Eq. (5).

From Eqs. (14), (15) and (6), upon integration over $x$, we obtain

$$\begin{aligned} \left[\delta S_{HT}^{Bj}\right]_{diquarks} &= \frac{\sin^2\Omega}{27}\left(D_1^2 + Q^2D_1D_3\right) \\ &\times \left\{4 + \frac{Q^2}{m_N^2}\int_0^1 \frac{dx}{x^2}\ f_{V_{uu}}(x)\right\}\,, \end{aligned} \tag{16}$$

which, via Eqs. (5) and (7), yields the numerical estimates at the $Q^2$ values [in (GeV/c)$^2$] for which data are available:

$$\begin{aligned} \left[\delta S_{HT}^{Bj}(Q^2 = 2.0)\right]_{diquarks} &\simeq 0.2\ \times 10^{-2} \\ \left[\delta S_{HT}^{Bj}(Q^2 = 4.6)\right]_{diquarks} &\simeq 0.5\ \times 10^{-3}\,. \end{aligned} \tag{17}$$

The prediction of the model in the full range $1 \leq Q^2 \leq 10$ (GeV/$c$)$^2$ can be found in Ref. [21].

We notice that the higher-twist contributions to the Bjorken sum rule, evaluated in the framework of the quark-diquark model of the nucleon, turn out to be quite small. They are small, and opposite in sign, even when compared with the perturbative QCD higher order corrections of Eqs. (8) and (9), namely with $a_3[E_{NS}(Q^2)-1]/6$.

$$\frac{\left[\delta S_{HT}^{Bj}(Q^2)\right]_{diquarks}}{a_3[1-E_{NS}(Q^2)]/6} \simeq 7\% \;\; (Q^2=2) \quad \text{and} \quad 2\% \;\; (Q^2=4.6)\,. \tag{18}$$

# 4 Diquark contribution to Gottfried sum rule

Similarly, one can compute, within the same model and using the same set of parameters, higher-twist contributions [22] to Gottfried sum rule:

$$S_G \equiv \int_0^1 \frac{dx}{x}\,[F_2^p(x,Q^2) - F_2^n(x,Q^2)] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\,[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)]\,. \tag{19}$$

Infact, in order to extract a reliable value of $\int dx\,[\bar{u}(x,Q^2)-\bar{d}(x,Q^2)]$ from Eq. (19) one should take into account all possible corrections, both perturbative QCD ones and higher-twist ones. The former are known to be rather small, less than 1% , and we give here an estimate of the latter; they also will turn out to be negligibly small, so that Eq. (19) can be safely used to extract precise information on the isospin asymmetry of the nucleon sea.

In the quark-diquark model of the nucleon one obtains

$$\begin{aligned} \int_0^1 \frac{dx}{x}[F_2^p \;\; &- \;\; F_2^n]_{q-D} = \frac{1}{3} + \frac{2}{3}\int_0^1 dx\,[\bar{u}(x) - \bar{d}(x)] \\ &- \;\; \frac{4}{9}\sin^2\Omega\, D_1^2 + \frac{8}{27}\sin^2\Omega \int_0^1 dx\, f_{V_{uu}}(x) \\ &\times \;\; \left\{ \left[ D_1 + Q^2\left(1+\frac{Q^2}{4m_N^2x^2}\right) D_3 \right]^2 + 2\left(1+\frac{Q^2}{4m_N^2x^2}\right) D_1^2 \right\}, \end{aligned} \tag{20}$$

so that

$$\begin{aligned} [\delta S_{HT}^G]_{diquarks} \;\; &= \;\; \frac{4}{9}\sin^2\Omega \left[ D_1^2 + \frac{4}{3}Q^2 D_1 D_3 + \frac{2}{3}Q^4 D_3^2 \right] \\ &+ \;\; \frac{8}{27}\sin^2\Omega\,\frac{Q^2}{2m_N^2}\left[D_1^2 + Q^2 D_1 D_3 + Q^4 D_3^2\right] \int_0^1 \frac{dx}{x^2} f_{V_{uu}}(x) \\ &+ \;\; \frac{8}{27}\sin^2\Omega\,\frac{Q^8}{16m_N^4} D_3^2 \int_0^1 \frac{dx}{x^4} f_{V_{uu}}(x)\,. \end{aligned} \tag{21}$$

Eqs. (21) and (5)-(7) give, at $Q^2 = 4$ (GeV/$c$)$^2$,

$$[\delta S_G]_{diquarks}\,(Q^2=4) \simeq 0.6 \;\times 10^{-2}\,. \tag{22}$$

# 5 Comments and conclusions

Higher-twist diquark contributions, both to Bjorken and Gottfried sum rules (Eqs. (17) and 22) respectively) turn out to be very small. This is due to some intrinsic features of the quark-diquark model of the nucleon: the strong $SU(6)$ violation ($\sin^2\Omega = 0.19$) favouring scalar diquarks (notice that only vector diquarks contribute to Eqs. (16) and (21)); the mass scale of the vector diquark form factor which turns out to be small, $Q_V^2 = 1.21$ (GeV/c)$^2$, corresponding to a large size, and the vector diquark $x$ distribution which is found to be peaked at $x \simeq 0.7$, suggesting that vector diquarks consist of two almost uncorrelated quarks.

This conclusion is confirmed by computing also the diquark contribution to the first moment of $g_1^p(x)$ alone, *i.e.*, $\Gamma_1^p = \int_0^1 dx\, g_1^p(x)$. A sizeable diquark contribution to $\Gamma_1^p$ would indicate that the tiny results obtained above for the Bjorken sum, Eqs. (17), are only due to a strong cancellation between the proton and the neutron contributions. However, an explicit calculation shows that diquark contributions to $\Gamma_1^p$ are comparable to those found for the Bjorken sum rule, rejecting this possibility.

We have summarized recent results on the evaluation of higher-twist contributions in DIS in terms of a quark–diquark model for the nucleon [23]. Such a work has consistently been performed within the same, physically motivated, phenomenological framework, within which it is possible to evaluate higher-twist effects (and not only the leading ones) in electron – and neutrino – initiated deep inelastic processes. In particular, we find that the diquark contributions to the Bjorken and Gottfried sum rules turn out to be quite small. This clarifies and makes more reliable both the use of the Bjorken sum rule in the experimental measurement of the strong coupling constant and of the Gottfried sum rule in the determination of the isospin asymmetry of the quark sea.

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