Deep inelastic ratio $R = \frac{\sigma_L}{\sigma_T}$ and the possible existence of scalar partons in the nucleon

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Abstract

We have performed several fits to find the ratio $R = \frac{\sigma_L}{\sigma_T}$ in different phenomenological models. Our fits seem to leave no room for possible admixture of scalar partons inside the nucleon.
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The aim of this paper is to determine the possible admixture of charged scalar partons in the nucleon. One is able to get such information considering the ratio of virtual photon cross sections $\sigma_L/\sigma_T$ in the deep-inelastic scattering. This ratio $R$ is proportional to the longitudinal structure function $F_L$,

$$R(x, Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{F_L(x, Q^2)}{2xF_1(x, Q^2)} = \frac{(1 + \frac{4M^2x^2}{Q^2})F_2(x, Q^2) - 2xF_1(x, Q^2)}{2xF_1(x, Q^2)}.$$ (1)

In order to get $R(x, Q^2)$ from the data we have performed several phenomenological fits. We have used all deep-inelastic experimental points for $Q^2 > 1\text{GeV}^2 [2, 3, 4]$, including the latest from the NMC Collaboration [4], which cover the kinematical range: $0.0045 \leq x \leq 0.7, 1\text{GeV}^2 \leq Q^2 \leq 70\text{GeV}^2$.

In the naive parton model (but with an inclusion of transverse momenta of nucleon constituents) one gets for the ratio $R$ the formula [1]

$$R(x, Q^2) = \frac{4M^2_T(x)}{Q^2},$$ (2)

where $M^2_T$ is a quark transverse mass squared. Let us parametrize $R$ as follows:

$$R(x, Q^2) = \frac{4M^2_T(x, Q^2)}{Q^2}.$$ (3)

Then, in the naive parton model we get

$$M^2_T(x, Q^2)_{NQM} = m^2_q + k^2_T(x).$$ (4)

The leading order QCD radiative corrections to this picture give in addition

$$M^2_T(x, Q^2)_{QCD} = \alpha_s(Q^2)Q^2 f_{QCD}(x, Q^2),$$ (5)

where $f_{QCD}$ is known if the parton (i.e. quark and gluon) distributions are available (see e.g. [3]). If we define [3]

$$F(x, Q^2) = x \sum_a e_a^2[q_a(x, Q^2) + \bar{q}_a(x, Q^2)],$$ (6)

we obtain in LO QCD for electromagnetic interactions:

$$f_{QCD}(x, Q^2) = \frac{x^2 \int_1^x \frac{dy}{y} F(x, Q^2)}{3\pi F(x, Q^2)} + \frac{x^2 \sum_{a=1}^{n_F} e_a^2 \int_1^y \frac{dy}{y} (y-x) G(x, Q^2)}{2\pi F(x, Q^2)},$$ (7)
where $G(x, Q^2)$ is the gluon distribution inside a nucleon and we sum over $n_F$ quark flavors.

Because the contribution to $M_T^2$, coming from QCD radiative corrections, is of order $\alpha_s Q^2$, it is usually bigger that the term calculated in the parton model which is of order $M_N^2$ ($M_N$ stands for nucleon mass).

If we take into account the possible existence of charged scalar partons inside the nucleon, we get an additional term

$$M_T^2(x, Q^2)_{SC} = Q^2 f_{SC}(x, Q^2),$$

where the unknown function $f_{SC}$ is connected to the function $\gamma(x)$ introduced in ref.[1]:

$$f_{SC}(x) = \frac{1 - \gamma(x)}{4\gamma(x)}.$$  \hspace{1cm} (9)

Hence, because of different $Q^2$ dependence of all three terms (see eqs.(4,5,8)) it is, in principle, possible to extract an information about scalar parton contribution.

A priori, scalar constituents might enter into the nucleon structure in different ways. Let us mention two options corresponding to two possible variants in the origin of these scalars.

(i) They could appear in an extended nucleon sea as squark-antisquark pairs $\tilde{q}\tilde{q}$ or, alternatively, as some other quarklike scalar-antiscalar pairs $y\bar{y}$. In particular, the latter partons $y$ might be the quarklike scalars named recently "yukawions" by one of us [7].

(ii) In a composite model of $u$ and $d$ quarks interpreted as bound states of a spin-1/2 preon $U$ or $D$ and a spin-0 preon $\phi$, the scalars $\phi$ could manifest in a generalized nucleon sea as $\phi\bar{\phi}$ pairs, and/or in a generalized nucleon valence fraction as single $\phi$ constituent arising in a dissociation process $u,d \rightarrow U,D + \phi$ [8]. In particular, the spin-1/2 preon $U$, $D$ might carry the electric charge 1 or 0, respectively, the lepton number $L = -1$ and no color, while the spin-0 preon $\phi$ would be a leptoquark with the electric charge -1/3 and the baryon and lepton numbers $B=1/3$ and $L=1$ [8]. Note that such $U$ and $D$ preons, together with the $\nu_e$ and $e^-$ leptons treated as elementary, would form an anomaly-free set of fundamental fermions (of the first family).

It is intuitively clear that, in the case of relatively heavy scalars, their role in deep inelastic scattering off the nucleon should increase with $Q^2$. Though
it does not prove to be true so far, this is especially suggestive in the case of option (ii) based on a picture of quarks $u$ and $d$ dissociating into their preons.

In our analysis we have repeated, first of all, the phenomenological fit presented in ref. [10] with inclusion of new data from the NMC collaboration [4]. The parametrization in such a fit is:

$$R(x, Q^2) = \frac{b_1}{\log(\frac{Q^2}{0.04})} \left[ 1 + \frac{12Q^2}{Q^2 + 1.0125^2 + x^2} \right] + \frac{b_2}{Q^2} + \frac{b_3}{Q^4 + 0.3^2}, \quad (10)$$

where $Q^2$ is in the GeV$^2$ units. The first term simulates the LO QCD prediction, the second and the third mimic twist effects. However, such parametrization does not take into account that ratio $R$ can be different for different nucleon targets. On the other hand, present experimental results suggest $R_d \simeq R_p$ [2].

The parameters in our first fit, giving $\chi^2$/d.o.f. $= 143/174 \simeq 0.82$, are (in parenthesis we quote parameters obtained in [11]):

$$b_1 = 0.041 \pm 0.006 \quad (0.0635),$$
$$b_2 = 0.592 \pm 0.009 \quad (0.5747),$$
$$b_3 = -0.331 \pm 0.010 \quad (-0.3534). \quad (11)$$

Next, we have tried to incorporate the term which comes from hypothetical, electromagnetic active, scalar partons. We have modeled the unknown function $f_{SC}(x, Q^2)$ (eq.(7)) very simply, namely as a combination of only two functions $F(x, Q^2)$ (eq.(6)) and $F_{val}(x, Q^2)$, where

$$F_{val}(x, Q^2) = x \sum_a e_a^2[q_a(x, Q^2) - \bar{q}_a(x, Q^2)] \quad (12)$$

describes valence quarks, provided the quark and antiquark distribution in the sea are identical. We propose for scalar parton contribution the following ansatz:

$$(M^2_{T})_{SC} = \frac{1}{4} p Q^2 \frac{\lambda F_{val}(x, Q^2) + \mu F(x, Q^2)}{F(x, Q^2)}, \quad (13)$$

where we choose $\lambda=1$ and $\mu = 0$, what corresponds to the conjecture that scalar partons are distributed similarly to valence quarks. On the other hand, it turns out that such a choice, where $p$ is the only parameter, gives
the optimal fit to data. For such a parametrization the $\chi^2$ value is not changed ($\chi^2 \simeq 143$) and leads to the value $\chi^2/d.o.f. = 143/173 \simeq 0.83$ that is worse than in the previous case. The parameter $p$ which plays roughly the role of probability for finding scalar parton inside a nucleon (see e.g. [4]) is $p = 0.14 \pm 0.48\%$ i.e., consistent with zero. For quarks and antiquarks we used parton distributions proposed by the authors of ref. [11].

The second type of model for the ratio $R$ discussed here is the leading order QCD formula (for four flavors) with inclusion of simple parametrization of the twist effects (the third and the fourth term in the following expression):

$$R(x, Q^2) = \frac{4x^2}{3\pi} \alpha_s(Q^2) \int_1^x \frac{dy}{y^3} F(x, Q^2) +$$

$$+ \frac{20x^2}{9\pi} \int_1^x \frac{dy}{y^3} (y - x) G(x, Q^2) + \frac{4m_T^2}{Q^2} + \frac{W}{Q^4}. \tag{14}$$

Here, we consider $m_T^2$ and $W$ as two parameters (i.e., constants independent of $x$; for $m_T^2$ we follow a conjecture of refs. [12, 6]).

Taking the quark and gluon distribution from GRV fit [11], we get $\chi^2/d.o.f. = 141/153 \simeq 0.92$, and

$$m_T^2 = (0.310 \pm 6 \text{ MeV})^2,$$

$$W = -(0.69 \pm 0.01 \text{ GeV})^4. \tag{15}$$

Performing the last fit we have not included the neutrino data from the CDHSW collaboration [3]. If we add to such a fit a new term, which comes from the possible admixture of scalar constituents inside a nucleon (see eq.(13)) we get a similar values for $\chi^2$ and for parameters $m_T^2$ and $W$, whereas the parameter $p$ is consistent with zero ($p \simeq 0.25 \pm 0.50\%$). The best fit is obtained by analyzing the data for $Q^2 \geq 10 \text{ GeV}^2$ only (this enables us to get rid of unknown twist contributions). Then $\chi^2/d.o.f. = 40/58 \simeq 0.69$ and

$$m_T^2 = (0.39 \text{ GeV})^2,$$

$$W = -(1.22 \text{ GeV})^4. \tag{16}$$

whereas $p$ is still consistent with zero.

In figures 1 and 2 we compare our fits, eqs.(10) and (14) to experimental data for definite $Q^2$ ($Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 45 \text{ GeV}^2$). One sees that the difference between them is visible only for small $x$. In figure 3 the curves for
the second fit, eq.(14), calculated for different targets (proton and deuteron), are compared with the experimental points for 

$$Q^2 = 10 \text{ GeV}^2.$$ 

Figure 1: The comparison of formulae: eq.(10) with parameters (11) and eq.(14) with parameters (15) ($R_{ph.}$ and $R_{QCD}$, respectively) with the experimental data for $Q^2 = 10 \text{ GeV}^2$. 

Figure 2: The comparison of formulae: eq.(10) with parameters (11) and eq.(14) with parameters (15) ($R_{ph.}$ and $R_{QCD}$, respectively) with the experimental data for $Q^2 = 45 \text{ GeV}^2$. 


In conclusion, we have analyzed two different models for ratio $R$, one phenomenological and one inspired by QCD with twist corrections added, getting no sign of existence of scalar constituents inside the nucleon.

![Figure 3](image_url)

**Figure 3**: The comparison of formulae eq.\((14)\), calculated for different targets (proton: $R^p$ and deuteron: $R^d$) with the experimental data for $Q^2 = 10 \text{ GeV}^2$.

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