The Quark Spin Distributions of the Nucleon

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Abstract

The quark helicity measured in polarized deep inelastic scattering is different from the quark spin in the rest frame of the nucleon. We point out that the quark spin distributions $\Delta q_{RF}(x)$ are connected with the quark helicity distributions $\Delta q(x)$ and the quark transversity distributions $\delta q(x)$ by an approximate relation: $\Delta q_{RF}(x) + \Delta q(x) = 2\delta q(x)$. This relation will be useful in order to measure the rest frame (or quark model) spin distributions of the nucleon once the quark helicity distributions and quark transversity distributions are themselves measured. We also calculate the $x$-dependent quark transversity distributions $\delta q(x)$ and quark spin distributions $\Delta q_{RF}(x)$ in a light-cone SU(6) quark-spectator model, and present discussions on possible effect from the sea quark-antiquark pairs.

To appear in Physics Letters B
1 Introduction

The spin content of the proton has received increasing attention since the observation of the Ellis-Jaffe sum rule violation in the experiments of polarized deep inelastic scattering (DIS) of leptons on the nucleon at CERN, DESY and SLAC (For recent reviews on the data see [1]). From the naive quark model we know that the three valence quarks provide the quantum numbers of the proton, thus the sum of the quark spins should be equal to the proton spin. However, it was found from the observed value of the Ellis-Jaffe integral that the sum of quark helicities is much smaller than 1/2. This gave rise to the proton “spin puzzle” or “spin crisis” since one usually identifies the “quark helicity” observed in polarized DIS with the “quark spin”. However, it has been pointed out in Ref. [2, 3] that the quark helicity ($\Delta q$) observed in polarized DIS is actually the quark spin defined in the light-cone formalism and it is different from the quark spin ($\Delta q_{RF}$) as defined in the quark model (or rest frame of the nucleon). Thus the small quark helicity sum observed in polarized DIS is not necessarily in contradiction with the quark model in which the proton spin is provided by the valence quarks [4].

From another point of view, the sea quarks of the nucleon seem to have non-trivial non-perturbative properties [5] that may be related to a number of empirical anomalies such as the Gottfried sum rule violation [6], the strange quark content of the nucleon [1, 8], the large charm quark content at high $x$ [9], as well as the Ellis-Jaffe sum rule violation. There are also indications that the gluons play an important role in the spin content of the proton [10]. Therefore the situation concerning the spin content of the proton might be more complicated than the naive quark model picture in which the spin of the proton is carried by the three valence quarks.

It would be helpful in order to clarify this situation if one could find a way to measure $\Delta q_{RF}$, the quark spin in the rest frame of the nucleon (or quark model). It is the purpose of this paper to point out an approximate relation that can be used to measure $\Delta q_{RF}$:

$$\Delta q_{RF}(x) + \Delta q(x) = 2\delta q(x),$$  \hspace{1cm} (1)

where $\Delta q(x)$ and $\delta q(x)$ are the corresponding quark helicity and transversity dis-
tributions, related to the axial quark current $\bar{q}\gamma^\mu\gamma^5 q$ and the tensor quark current $\bar{q}\sigma^{\mu\nu}i\gamma^5 q$ \[1\] respectively. We recall that the quark helicity distributions $\Delta q(x)$ are extracted from the spin-dependent structure functions $g_1^N(x)$, defined as $g_1^N(x) = 1/2 \sum_q e_q^2 \Delta q(x)$, obtained in several polarized Deep Inelastic Scattering experiments\[12\].

The transversity distribution $\delta q(x)$ measures the difference of the number of quarks with transverse polarization parallel and antiparallel to the proton transverse polarization. It can be obtained, in principle, by measuring a Drell-Yan process in a $pp$ collision where both protons are transversely polarized \[11, 13, 14\], but it seems rather difficult and a different method has been proposed \[15\]. Assuming that $\Delta q(x)$ and $\delta q(x)$ have been measured, we can then obtain the quark spin distributions $\Delta q_{RF}(x)$ by using Eq. (1). We will show how Eq. (1) can be derived by making use of the Melosh-Wigner rotation connecting the ordinary quark spin and the light-cone quark spin. We will also make numerical predictions of the $x$-dependent distributions $\delta q(x)$ and $\Delta q_{RF}(x)$ in a light-cone SU(6) quark-spectator model and present some relevant discussions on the effect from the sea quark-antiquark pairs.

2 The Melosh-Wigner rotation

It is proper to describe deep inelastic scattering as the sum of incoherent scatterings of the incident lepton on the partons in the infinite momentum frame or in the light-cone formalism. We will work along with the developments in refs. \[2, 3, 16\], by taking into account the effect due to the Melosh-Wigner rotation \[17, 18\] which is an important ingredient in the light-cone formalism \[19\]. The axial charge $\Delta q = \int dx \Delta q(x)$ measured in polarized deep inelastic scattering is defined by the axial current matrix element

$$\Delta q = <p, \uparrow |\bar{q}\gamma^+\gamma^5 q|p, \uparrow> .$$

(2)

In the light-cone or quark-parton descriptions, $\Delta q(x) = q^\uparrow(x) - q^\downarrow(x)$, where $q^\uparrow(x)$ and $q^\downarrow(x)$ are the probability of finding a quark or antiquark with longitudinal momentum fraction $x$ and polarization parallel or antiparallel to the proton helicity in the infinite
momentum frame. However, in the nucleon rest frame one finds [2, 3],

\[ \Delta q(x) = \int [d^2k_\perp] M_q(x, k_\perp) \Delta q_{RF}(x, k_\perp), \tag{3} \]

with

\[ M_q(x, k_\perp) = \frac{(k^+ + m)^2 - k_\perp^2}{(k^+ + m)^2 + k_\perp^2}, \tag{4} \]

where \( M_q(x, k_\perp) \) being the contribution from the relativistic effect due to the quark transverse motions (or Melosh-Wigner rotation effect), \( q_{s_z=\frac{1}{2}}(x, k_\perp) \) and \( q_{s_z=-\frac{1}{2}}(x, k_\perp) \) being the probabilities of finding a quark and antiquark with rest mass \( m \) and transverse momentum \( k_\perp \) and with spin parallel and anti-parallel to the rest proton spin, one then has, \( \Delta q_{RF}(x, k_\perp) = q_{s_z=\frac{1}{2}}(x, k_\perp) - q_{s_z=-\frac{1}{2}}(x, k_\perp) \), and \( k^+ = x M \), where \( M^2 = \sum_i (m_i^2 + k_{\perp i}^2)/x_i \). The Melosh-Wigner rotation factor \( M_q(x, k_\perp) \) ranges from 0 to 1; thus \( \Delta q \) measured in polarized deep inelastic scattering cannot be identified with \( \Delta q_{RF} \), the spin carried by each quark flavor in the proton rest frame or the quark spin in the quark model.

The same technique by making use of the Melosh-Wigner rotation effect has been applied to the quark tensor charge [16] which is calculated from

\[ 2\delta q = < p, \uparrow | \bar{q}_\lambda \gamma^+ \gamma_\perp q_{-\lambda} | p, \downarrow >, \tag{5} \]

with \( \lambda = + \) and \( \gamma^_\perp = \gamma^1 + i\gamma^2 \), and it is found that the quark transversity distribution equals to

\[ \delta q(x) = \int [d^2k_\perp] \tilde{M}_q(x, k_\perp) \Delta q_{RF}(x, k_\perp), \tag{6} \]

with

\[ \tilde{M}_q(x, k_\perp) = \frac{(k^+ + m)^2}{(k^+ + m)^2 + k_\perp^2} \tag{7} \]

being the correction factor from the Melosh-Wigner rotation [16]. From Eqs. (6) and (7) one easily finds the relation [16]

\[ 1 + M_q = 2\tilde{M}_q. \tag{8} \]

*In Eq. (7), \( \tilde{M}_q(x, k_\perp) \) has additional terms like \( k_{\perp 1}^2 - k_{\perp 2}^2 \) in the numerator, where \( k_\perp = (k_1, k_2) \) is the transverse momentum of the struck quark. These terms vanish upon integration over the azimuth of \( k_\perp \).
Combining Eqs. (3), (6), and (8), one has Eq. (1).

Eq. (8) is valid in a quite general framework of the light-cone quark model \[3, 18\], and is in fact non-perturbative. We point out that correction factors similar to \(M_q\) and \(\bar{M}_q\) have been also found in other papers \[14, 20\] on the quark distribution functions \(\Delta_q(x)\) and \(\delta q(x)\). Though the explicit expressions for the \(M_q\) and \(\bar{M}_q\) and the physical significances are different, Eq. (8) also holds in these different approaches. Recently there has been also a proof of the above suggested relation Eq. (1) in a QCD Lagrangian based formalism\[21\]. Thus Eq. (8), and consequently its extension to Eq. (1), might be considered as a relation with general physical implications. Since \(\Delta q(x)\) and \(\delta q(x)\) have different evolution behaviors, the relation Eq. (1) should be considered as valid at some model energy scale \(Q^2_0\) \[14\], such as \(Q^2_0 \approx 1 \to 5 \text{ GeV}^2\) in our case. Although it has a similar appearance, Eq. (1) is not a saturation of the inequality \[22\]:

\[
q(x) + \Delta q(x) \geq 2|\delta q(x)|,
\]

since \(\Delta q_{RF}(x)\) is clearly not the same as \(q(x)\).

3 The light-cone SU(6) quark-spectator model

We now discuss the \(x\)-dependent quark distributions \(\Delta q_{RF}(x)\) and \(\delta q(x)\) in a light-cone SU(6) quark-spectator model \[4\], which can be considered as a revised version of the quark-spectator model developed in \[23\]. The unpolarized valence quark distributions \(u_v(x)\) and \(d_v(x)\) are given in this model by

\[
\begin{align*}
u_v(x) &= \frac{1}{2}a_S(x) + \frac{1}{6}a_V(x); \\
d_v(x) &= \frac{1}{3}a_V(x),
\end{align*}
\]

where \(a_D(x)\) (\(D = S\) for scalar spectator or \(V\) for axial vector spectator) is normalized such that \(\int_0^1 dx a_D(x) = 3\), and it denotes the amplitude for quark \(q\) to be scattered while the spectator is in the diquark state \(D\). Exact SU(6) symmetry provides the relation \(a_S(x) = a_V(x)\), which implies the valence flavor symmetry \(u_v(x) = 2d_v(x)\). This gives the prediction \(F_2^n(x)/F_2^p(x) \geq 2/3\) for all \(x\), which is ruled out by the
experimental observation $F_2^n(x)/F_2^p(x) < 1/2$ for $x \to 1$. The mass difference between the scalar and vector spectators can reproduce the $u$ and $d$ valence quark asymmetry that accounts for the observed ratio $F_2^n(x)/F_2^p(x)$ at large $x$. This supports the quark-spectator picture of deep inelastic scattering in which the difference between the mass of the scalar and vector spectators is important in order to reproduce the explicit SU(6) symmetry breaking, while the bulk SU(6) symmetry of the quark model still holds.

From the above discussions concerning the Melosh-Wigner rotation effect, we can write the quark helicity distributions for the $u$ and $d$ quarks as

$$\Delta u_v(x) = u^\uparrow_v(x) - u^\downarrow_v(x) = -\frac{1}{18} a_V(x) M_V(x) + \frac{1}{2} a_S(x) M_S(x);$$

$$\Delta d_v(x) = d^\uparrow_v(x) - d^\downarrow_v(x) = -\frac{1}{9} a_V(x) M_V(x),$$

in which $M_S(x)$ and $M_V(x)$ are the Melosh-Wigner correction factors for the scalar and axial vector spectator-diquark cases. They are obtained by averaging Eq. (4) over $k_\perp$ with $M^2 = (m^2 + k^2_\perp)/x + (m_D^2 + k^2_\perp)/x$, where $m_D$ is the mass of the diquark spectator, and are unequal due to unequal spectator masses $\to$ unequal $k_\perp$ distributions. From Eq. (10) one gets

$$a_S(x) = 2u_v(x) - d_v(x);$$

$$a_V(x) = 3d_v(x).$$

Combining Eqs. (11) and (12) we have

$$\Delta u_v(x) = [u_v(x) - \frac{1}{2} d_v(x)] M_S(x) - \frac{1}{6} d_v(x) M_V(x);$$

$$\Delta d_v(x) = -\frac{1}{3} d_v(x) M_V(x).$$

Thus we arrive at simple relations [4] between the polarized and unpolarized quark distributions for the valence $u$ and $d$ quarks. The relations (13) can be considered as the results of the conventional SU(6) quark model, and which explicitly take into account the Melosh-Wigner rotation effect [2, 3] and the flavor asymmetry introduced by the mass difference between the scalar and vector spectators [1].
The extension of relations Eq. (13) to the quark spin distributions $\Delta q_{\text{RF}}(x)$ and transversity $\delta q(x)$ is straightforward: we can simply replace $M_S(x)$ and $M_V(x)$ by 1 for $\Delta q_{\text{RF}}(x)$ and by $\tilde{M}_S(x)$ and $\tilde{M}_V(x)$ for $\delta q(x)$,

\[
\begin{align*}
\Delta u_v^{\text{RF}}(x) &= u_v(x) - \frac{2}{3}d_v(x); \\
\Delta d_v^{\text{RF}}(x) &= -\frac{1}{3}d_v(x); \\
\delta u_v(x) &= [u_v(x) - \frac{1}{2}d_v(x)]\tilde{M}_S(x) - \frac{1}{6}d_v(x)\tilde{M}_V(x); \\
\delta d_v(x) &= -\frac{1}{3}d_v(x)\tilde{M}_V(x).
\end{align*}
\] (14)

We notice that the quark spin distributions $\Delta q_{\text{RF}}(x)$, i.e., Eq. (14), are connected with the unpolarized quark distributions without any model parameter. Thus any evidence for the invalidity of Eq. (14), by combining together the measured $\Delta q_v(x)$ and $\delta q_v(x)$, will provide a clean signature for new physics beyond the SU(6) quark model.

The $x$-dependent Melosh-Wigner rotation factors $M_S(x)$ and $M_V(x)$ have been calculated [4] and an asymmetry between $M_S(x)$ and $M_V(x)$ was found. The calculated polarization asymmetries $A_1^N = 2xg_1^N(x)/F_2^N(x)$ including the Melosh-Wigner rotation have been found [4] to be in reasonable agreement with the experimental data, at least for $x \geq 0.1$. A large asymmetry between $M_S(x)$ and $M_V(x)$ leads to a better fit to the data, than that obtained from a small asymmetry. Therefore it is reasonable to expect that the calculated $\delta q(x)$ and $\Delta q_{\text{RF}}(x)$ may lead to predictions close to the real situation. In Fig. (1) we present the calculated $\Delta q(x)$, $\delta q(x)$ and $\Delta q_{\text{RF}}(x)$ for the $u$ and $d$ valence quarks. From Eqs. (3), (6) and Fig. (1) we observe the inequalities,

\[
|\Delta q_{\text{RF}}(x)| \geq |\delta q(x)| \geq |\Delta q(x)|.
\] (16)

However, the different evolution behaviors of $\delta q(x)$ and $\Delta q(x)$ may break the inequality $|\delta q(x)| \geq |\Delta q(x)|$ at large $Q^2$ [14]. This interesting hierarchy is specific of this model and is not necessarily satisfied in general.
Figure 1: The x-dependent quark spin distributions $x\Delta q_{RF}(x)$ (solid curves), transversity distributions $x\delta q(x)$ (dashed curves), and helicity distributions $x\Delta q(x)$ (dotted curves) in the light-cone SU(6) quark-spectator model by using Eqs. (13-15), with the Glück-Reya-Vogt parameterization [24] of unpolarized quark distributions as input: (a) for $u$ quarks; (b) for $d$ quarks.

As we have pointed out, one should not confuse Eq. (1) with the saturation of the inequality (9), which is valid for each flavor, likewise for antiquarks. Eq. (1) only equals to the saturated (8) for the scalar spectator case, but not for the vector spectator case due to the fact that $q(x) \neq \Delta q_{RF}(x)$. Since $|\Delta q_{RF}(x)| \leq q(x)$, we may re-write from Eq. (1) another inequality

$$q(x) \geq |2\delta q(x) - \Delta q(x)|,$$

which is similar to, but different from, the inequality (8). Actually (8) is a stronger constraint than (17). Nevertheless, we point out without detailed argument here that
the inequality (9) is valid in the light-cone SU(6) quark model, even when the meson-baryon fluctuations, that will be considered in the next section, are also taken into account.

Since the Melosh-Wigner rotation factor $M$ is less than 1, we expect to find that $\sum_q \Delta q_{RF}$, where $\Delta q_{RF}$ is the first moment of $\Delta q_{RF}(x)$, will be much closer to 1 than the usual helicity sum $\Delta \Sigma = \sum_q \Delta q$, which experimentally is about 0.2, and whose departure from the quark model value of 1 originated the “spin crisis”. In this context it is interesting to notice that lattice QCD calculations gave an axial charge $\Delta \Sigma = 0.18 \pm 0.10$ [24] and a tensor charge $\delta \Sigma = 0.562 \pm 0.088$ [26]. Thus the spin carried by quarks from lattice QCD should be $\sum_q \Delta q_{RF} = 0.94 \pm 0.28$ from Eq. (1), and this supports the naive quark picture that the spin of the proton is mostly carried by quarks. In a quark model that does not contain antiquarks, $\sum_q \Delta q_{RF}$ will be strictly 1, but in general it will receive contributions other than the usual valence quarks. Thus it will be of great interest to develop a more refined quark model which can explain or predict its actual experimental value.

4 The sea quark-antiquark pairs

We still need to consider the higher Fock states for a better understanding of a number of empirical anomalies related to the nucleon sea quarks probed in deep inelastic scattering. The Ellis-Jaffe sum rule violation is closely related to the Gottfried sum rule violation, which implies an excess of $d\bar{d}$ pairs over $u\bar{u}$ pairs in the proton sea [6, 27]. This can be explained by the meson-baryon fluctuation picture of the nucleon sea [3, 27]: the lowest nonneutral $u\bar{u}$ fluctuation in the proton is $\pi^-(d\bar{u})\Delta^{++}(uuu)$, and its probability is small compared to the less massive nonneutral $d\bar{d}$ fluctuation $\pi^+(u\bar{d})n(udd)$. Therefore the dominant nonneutral light-flavor $q\bar{q}$ fluctuation in the proton sea is $d\bar{d}$ through the meson-baryon configuration $\pi^+(u\bar{d})n(udd)$. For the spin structure of the $q\bar{q}$ pairs from the meson-baryon fluctuation model, it is observed [3] that the net $d$ quark spin of the intrinsic $q\bar{q}$ fluctuation is negative, whereas the net $\bar{d}$ antiquark spin is zero.

The quark helicity distributions $\Delta q(x)$ and transversity distributions $\delta q(x)$ should
be measured for quarks and antiquarks separately for applying Eq. (1). Thus we need techniques that allow the measurement of $\Delta q(x)$ and $\delta q(x)$ for quarks and antiquarks. The antiquark contributions to $\Delta q$ and $\delta q$ are predicted to be zero in the meson-baryon fluctuation model \[5\] and in a broken-U(3) version of the chiral quark model \[28\]. There have been explicit measurements of the helicity distributions for the individual $u$ and $d$ valence and sea quarks by the Spin Muon Collaboration (SMC) \[12\]. The measured helicity distributions for the $u$ and $d$ antiquarks are consistent with zero, in agreement with the above predictions \[3, 28\]. The SMC data for the quark helicity distributions $\Delta u_v(x)$ and $\Delta d_v(x)$, which are actually $\Delta u(x) - \Delta \bar{u}(x)$ and $\Delta d(x) - \Delta \bar{d}(x)$, are still not precise enough for making detailed comparison, but the agreement of the SMC data with the calculated $\Delta u_v(x)$ turns out to be reasonable \[3\]. It seems that there is some evidence for an additional source of negative helicity contribution to the valence $d$ quark beyond the conventional quark model from the refined results by SMC \[12\]. This supports the prediction \[3\] that the measured $\Delta d(x) - \Delta \bar{d}(x)$ should receive additional negative contribution from the intrinsic $d$ sea quarks in comparison with the valence-dominant result presented in Fig. (1).

In case of symmetric quark-antiquark sea pairs, we may consider Eq. (1) as a relation that applies to valence quarks. The tensor charge, defined as $\delta Q = \int_0^1 dx [\delta q(x) - \delta \bar{q}(x)]$, receives only contributions from the valence quarks since those from the sea quarks and antiquarks cancel each other, due to the charge conjugation properties of the tensor current $\bar{q}\sigma^{\mu\nu}\gamma^5 q$. The helicity distributions for quarks and antiquarks can be measured in semi-inclusive deep inelastic processes separately \[12\], thus we can measure the valence quark helicity distributions defined by $\Delta q_v(x) = \Delta q(x) - \Delta \bar{q}(x)$ from experiment. We also notice that there is no clear way to strictly distinguish between the valence quarks and sea quarks for the $u$ and $d$ flavors, since one can have a symmetric quark-antiquark sea pairs by defining the valence quark $q_v = q - \bar{q}$ due to the excess of net $u$ and $d$ quarks in the nucleon. Eq. (1) is also valid for the above defined valence quarks (which should be actually $q - \bar{q}$) in case of non-zero spin contribution from antiquarks.

One interesting feature of the meson-baryon fluctuations is the strange quark-antiquark asymmetry from the virtual $K^+\Lambda$ pair of the proton \[3\]. The intrinsic
strangeness fluctuations in the proton wavefunction are mainly due to the intermediate $K^+\Lambda$ configuration since this state has the lowest off-shell light-cone energy and invariant mass. The intrinsic strange quark normalized to the probability $P_{K^+\Lambda}$ of the $K^+\Lambda$ configuration yields a fractional contribution $\Delta S_s = 2S_z(\Lambda) = -\frac{1}{3}P_{K^+\Lambda}$ to the proton spin, whereas the intrinsic antistrange quark gives a zero contribution: $\Delta S_{\bar{s}} = 0$. In case of symmetric strange quark-antiquark pairs, one shall predict a zero strange tensor charge. However, a non-zero strange tensor charge will arise from the strange quark-antiquark spin asymmetry due to the meson-baryon fluctuations and we predict a strange tensor charge $\delta s \approx -0.02 \rightarrow -0.03$ (similar to $\Delta s [5]$) corresponding to the probability $P_{K^+\Lambda} = 5 \rightarrow 10\%$.

5 Discussion and Summary

In this paper we have proposed an approximate relation that can be used to measure the quark spin distribution $\Delta q_{RF}(x)$, as implied in the quark model or in the rest frame of the nucleon. It will be very meaningful if a clear definition of this spin distribution or any other way for measuring this quantity can be found. It has been noticed recently [29] that the quark spin distribution defined in this paper is actually equivalent to $\Delta q(x) + 2L_q(x)$, where $\Delta q(x)$ is the quark helicity distribution and $L_q(x)$ is the quark orbital angular momentum obtained by calculating the matrix element of the operator $L_q = -i\gamma^+ k \times \nabla_k$. Thus $\Delta q_{RF}(x)$ is a quantity that can be calculated in an exact theoretical framework, such as lattice QCD, and might be measurable in the future. This means that Eq. (1) might be a practical relation that can be tested by other means.

In summary, we showed in this paper that the quark spin distributions $\Delta q_{RF}(x)$, in the rest frame of the nucleon, are connected with the quark helicity distributions $\Delta q(x)$ and the quark transversity distributions $\delta q(x)$ by an approximate but simple relation: $\Delta q_{RF}(x) + \Delta q(x) = 2\delta q(x)$. This relation will be useful to measure the quark spin distributions of the nucleon once the quark helicity distributions and quark transversity distributions are measured. It will be also very useful in order to check various models and will provide more information concerning the spin structure.
of the nucleon.

**Acknowledgments:** We would like to thank V. Barone, S.J. Brodsky, R. Jakob, K.-F. Liu, and P.J. Mulders for helpful discussions. This work is partially supported by National Natural Science Foundation of China under Grant No. 19605006, Fondecyt (Chile) under grant 1960536, by the cooperation programme ECOS-CONICYT between France and Chile under contract No. C94E04, by a Cátedra Presidencial (Chile), and by Fundación Andes (Chile).
References

[1] A. Brüll, Invited talk at Lepton Photon 1997, Hamburg July 1997; R. Windmolders, C. Young, D. Hasch, Invited talks at the Workshop, Deep Inelastic Scattering off polarized targets: Theory meets Experiment, Zeuthen September 1997.

[2] B.-Q. Ma, J. Phys. G 17 (1991) L53;
   B.-Q. Ma and Q.-R. Zhang, Z. Phys. C 58 (1993) 479.

[3] S.J. Brodsky and F. Schlumpf, Phys. Lett. B 329 (1994) 111.

[4] B.-Q. Ma, Phys. Lett. B 375 (1996) 320.

[5] See, e.g., S.J. Brodsky and B.-Q. Ma, Phys. Lett. B 381 (1996) 317, and references therein.

[6] NM Collab., P. Amaudruz et al., Phys. Rev. Lett. 66 (1991) 2712;
   M. Arneodo et al., Phys. Rev. D 50 (1994) R1.

[7] CTEQ Collab., J. Botts et al., Phys. Lett. B 304 (1993) 159.

[8] CCFR Collab., S.A. Rabinowitz et al., Phys. Rev. Lett. 70 (1993) 134;
   A.O. Bazarko et al., Z. Phys. C 65 (1995) 189.

[9] S.J. Brodsky, P. Hoyer, C. Peterson, and N. Sakai, Phys. Lett. B 93 (1980) 451;
   S.J. Brodsky, C. Peterson, and N. Sakai, Phys. Rev. D 23 (1981) 2745.

[10] See, e.g., G. Altarelli and G.G. Ross, Phys. Lett. B 212 (1988) 391;
    R.D. Carlitz, J.C. Collins, and A.H. Mueller, Phys. Lett. 214 (1988) 229;
    A.V. Efremov, J. Soffer, and O.V. Teryaev, Nucl. Phys. B 346 (1990) 97.

[11] J.P. Ralston and D.E. Soper, Nucl. Phys. B152 (1979) 109;
    X. Artru and M. Mekhfi, Z. Phys. C45 (1990) 669;
R.L. Jaffe and X. Ji, Phys.Rev.Lett. 67 (1991) 552;
J.L. Cortes, B. Pire and J.P. Ralston, Z. Phys. C55 (1992) 409.

The notation \( \delta q(x) \) in our paper actually corresponds to \( h_1(x) \) in some other papers.

[12] SM Collab., B. Adeva et al., Phys. Lett. B 369 (1996) 93; for most recent refined results, see, Phys. Lett. 420 (1998) 180;
SLAC-E154, K. Abe et al., Phys. Rev. Lett. 79 (1997) 26;
HERMES Collab., K. Ackerstaff et al., Phys. Lett. 404 (1997) 383.

[13] C. Bourrely and J.Soffer, Nucl. Phys. B 445 (1995) 341.

[14] V. Barone, T. Calarco, and A. Drago, Phys. Lett. 390 (1997) 287; Phys. Rev. D 56 (1997) 527.

[15] R.L. Jaffe, X. Jin and J. Tang, Phys. Rev. Lett. 80 (1998) 1166.

[16] I. Schmidt and J. Soffer, Phys. Lett. B 407 (1997) 331.

[17] H.J. Melosh, Phys. Rev. D 9 (1974) 1095;
E. Wigner, Ann. Math. 40 (1939) 149.

[18] See, also, e.g.,
L.A. Kondratyuk and M.V. Terent’ev, Yad.Fiz 31 (1980) 1087 [ Sov. J. Nucl. Phys. 31 (1980) 561];
P.L. Chung, F. Coester, B.D. Keister, and W.N. Polyzou, Phys. Rev. C 37 (1988) 2000;
W. Konen and H.J. Weber, Phys. Rev. D 41 (1990) 2201;
H.J. Weber, Ann. Phys. (N.Y.) 207 (1991) 417;
W. Jaus, Phys. Rev. D 41 (1990) 3394; D 44 (1991) 2851;
P.L. Chung and F. Coester, Phys. Rev. D 44 (1991) 229;
B.-Q. Ma, Z. Phys. A 345 (1993) 325;
F. Schlumpf, Phys. Rev. D 48 (1993) 4478;
F. Schlumpf and S.J. Brodsky, Phys. Lett. 360 (1995) 1.

T. Huang, B.-Q. Ma, and Q.-X. Shen, Phys. Rev. D 49 (1994) 1490;
B.-Q. Ma and T. Huang, J. Phys. G 21 (1995) 765;
F.-G. Cao, J. Cao, T. Huang, and B.-Q. Ma, Phys. Rev. D 55 (1997) 7107.

[19] See, e.g., S.J. Brodsky, H-C. Pauli, and S.S. Pinsky, Phys. Rept. 301 (1998) 299, and references therein.

[20] R. Jakob, P.J. Mulders, and J. Rodrigues, Nucl. Phys. A 626 (1997) 937.

[21] D. Qing, X.-S. Chen, and F. Wang, hep-ph/9802423.

[22] J. Soffer, Phys. Rev. Lett. 74 (1995) 1292.

[23] R. Carlitz, Phys. Lett. B 58 (1975) 345;
J. Kaur, Nucl. Phys. B 128 (1977) 219;
A. Schäfer, Phys. Lett. B 208 (1988) 175.

[24] M. Glück, E. Reya, and A. Vogt, Z. Phys. C 67 (1995) 433. We use the LO set at $Q^2 = 5$ GeV$^2$ in the calculations.

[25] M. Fukugita, Y. Kuramashi, M. Okawa, and A. Ukawa, Phys. Rev. Lett. 75 (1995) 2092.

[26] S. Aoki, M. Doui, T. Hatsuda, and Y. Kuramashi, Phys. Rev. D 56 (1997) 433.

[27] A.W. Thomas, Phys. Lett. B 126 (1983) 97;
E.M. Henley and G.A. Miller, Phys. Lett. B 251 (1990) 453;
S. Kumano, Phys. Rev. D 43 (1991) 59; D 43 (1991) 3067;
A. Signal, A.W. Schreiber, and A.W. Thomas, Mod. Phys. Lett. A 6 (1991) 271;
C. Bourrely et al., preprint CPT-97/P.3578, to appear in Prog. of Theor. Phys. and references therein.
[28] T.P. Cheng and L.F. Li, Phys. Rev. Lett. 74 (1995) 2872; Phys. Lett. B 366 (1996) 365.

[29] B.-Q. Ma and I. Schmidt, preprint USM-TH-74, {
hep-ph/9808202}. Phys. Rev. D 58 (1998) in press.