THE PROTON SPIN STRUCTURE IN A LIGHT-CONE QUARK-SPECTATOR-DIQUARK MODEL\textsuperscript{a}

BO-QIANG MA

\textit{Institute of High Energy Physics, Academia Sinica}

\textit{P. O. Box 918(4), Beijing 100039, China}

It is shown that the proton spin problem raised by the Ellis-Jaffe sum rule violation does not in conflict with the SU(6) quark model, provided that the relativistic effect from the quark transversal motions, the flavor asymmetry between the $u$ and $d$ valence quarks, and the intrinsic quark-antiquark pairs generated by the non-perturbative meson-baryon fluctuations of the nucleon sea are taken into account. The meson-baryon fluctuations of the nucleon sea provide a consistent picture for connecting the proton spin structure with a number of other anomalies observed in the proton’s structure, such as the flavor asymmetry of the nucleon sea implied by the violation of the Gottfried sum rule and the discrepancy between two different measurements of the strange quark distributions in the nucleon sea.

1 The Proton Spin Puzzle and the Wigner Rotation

1.1 The Violation of the Ellis-Jaffe Sum Rule and the Proton Spin “Crisis”

Parton sum rules and similar relations played important roles in the establishment of the quark-parton picture for nucleons in deep inelastic scattering. Thus any violation of a parton sum rule may of essential importance to reveal possible new content concerning our understanding of the underlying quark-gluon structure of hadrons.

Form the SU(6) quark model one would expect that the spin of the proton is fully provided by the valence quark spins. Therefore the observation of the Ellis-Jaffe sum rule violation received attention by its implication that the sum of the quark helicities is much smaller than the proton helicity. The EMC result of a much smaller integrated spin-dependent structure function data than that expected from the Ellis-Jaffe sum rule triggered the proton “spin crisis”, i.e., the intriguing question of how the spin of the proton is distributed among its quark spin, gluon spin and orbital angular momentum. It is commonly taken for granted that the EMC result implies that there must be some contribution due to gluon polarization or orbital angular momentum to the proton spin. For example, in the gluonic and the strange sea explanations of the EJSR breaking, the proton spin carried by the spin of quarks was estimated to be of about 70%.

\textsuperscript{a}Invited talk presented at the Diquarks 3rd Workshop, October 28-30, Villa Gualino, Torino, Italy. To appear in the proceedings (World Scientific) edited by M. Anselmino and E. Predazzi. hep-ph/9703425
in the former and of about 30% in the latter. It will be reported here based on previous works\textsuperscript{2−5}, however, that the proton spin problem raised by the Ellis-Jaffe sum rule violation does not in conflict with the SU(6) quark model in which the spin of the proton, when viewed in its rest reference frame, is provided by the vector sum of the quark spins, provided that the relativistic effect from the quark transversal motions\textsuperscript{2,3}, the flavor asymmetry between the \textit{u} and \textit{d} valence quarks\textsuperscript{4}, and the intrinsic quark-antiquark pairs generated by the non-perturbative meson-baryon fluctuations of the nucleon sea\textsuperscript{5} are taken into account.

1.2 The Relativistic Effect due to Quark Transversal Motions

As it is known, spin is essentially a relativistic notion associated with the space-time symmetry of Poincaré. The conventional 3-vector spin \( s \) of a moving particle with finite mass \( m \) and 4-momentum \( p_{\mu} \) can be defined by transforming its Pauli-Lubánski 4-vector \( \omega_{\mu} = 1/2J^{\rho\sigma}P^\nu\epsilon_{\nu\rho\sigma\mu} \) to its rest frame via a non-rotation Lorentz boost \( L(p) \) which satisfies \( L(p)p = (m, 0) \), by \((0, s) = L(p)\omega/m \). Under an arbitrary Lorentz transformation, a particle state with spin \( s \) and 4-momentum \( p_{\mu} \) will transform to the state with spin \( s' \) and 4-momentum \( p'_{\mu} \),

\[
    s' = R_\omega(A, p)s, \quad p' = A p, \tag{1}
\]

where \( R_\omega(A, p) = L(p')AL^{-1}(p) \) is a pure rotation known as Wigner rotation. When a composite system is transformed from one frame to another one, the spin of each constituent will undergo a Wigner rotation. These spin rotations are not necessarily the same since the constituents have different internal motion. In consequence, the sum of the constituent’s spin is not Lorentz invariant.

The key points for understanding the proton spin puzzle lie in the facts that the vector sum of the constituent spins for a composite system is not Lorentz invariant by taking into account the relativistic effect of Wigner rotation, and that it is in the infinite momentum frame the small EMC result was interpreted as an indication that quarks carry a small amount of the total spin of the proton. From the first fact we know that the vector spin structure of hadrons could be quite different in different frames from relativistic viewpoint. We thus can naturally understand the proton “spin crisis” because there is no need to require that the sum of the quark spins be equal to the spin of the proton in the infinite momentum frame, even if the vector sum of the quark spins equals to the proton spin in the rest frame.

The effect due to the Wigner rotation can be best understood from the light-cone spin structure of the pion. It has been shown\textsuperscript{6−8} that there are
higher helicity \((\lambda_1 + \lambda_2 = \pm 1)\) components in the light-cone spin space wavefunction for the pion besides the usual helicity \((\lambda_1 + \lambda_2 = 0)\) component. Therefore the light-cone wavefunction for the lowest valence state of pion can be expressed as

\[
|\psi_{\pi}^{q} \rangle = \psi(x, \vec{k}_\perp, \uparrow) |\uparrow \downarrow\rangle + \psi(x, \vec{k}_\perp, \downarrow) |\downarrow \uparrow\rangle + \psi(x, \vec{k}_\perp, \uparrow, \uparrow) |\uparrow \uparrow\rangle + \psi(x, \vec{k}_\perp, \downarrow, \downarrow) |\downarrow \downarrow\rangle,
\]

(2)

It is interesting to be noticed that the light-cone wave function (2) is the correct pion spin wave function since it is an eigenstate of the total spin operator \((\hat{S}^F)^2\) in the light-cone formalism.

It is thus necessary to clarify what is meant by the quantity \(\Delta q\) defined by \(\Delta q = \langle P, S | \vec{q} \cdot \gamma \uparrow \gamma \downarrow q | P, S \rangle\), where \(\vec{S}\) is the proton polarization vector. \(\Delta q\) can be calculated from \(\Delta q = \langle P, S | \vec{q} \cdot \gamma \uparrow \gamma \downarrow q | P, S \rangle\) since the instantaneous fermion lines do not contribute to the + component. One can easily prove, by expressing the quark wave functions in terms of light-cone Dirac spinors (i.e., the quark spin states in the infinite momentum frame), that

\[
\Delta q = \int_0^1 dx [q^\uparrow(x) - q^\downarrow(x)],
\]

(3)

where \(q^\uparrow(x)\) and \(q^\downarrow(x)\) are the probabilities of finding, in the proton infinite momentum frame, a quark or antiquark of flavor \(q\) with fraction \(x\) of the proton longitudinal momentum and with polarization parallel or antiparallel to the proton spin, respectively. However, if one expresses the quark wave functions in terms of conventional instant form Dirac spinors (i.e., the quark spin state in the proton rest frame), it can be found, that

\[
\Delta q = \int d^3\vec{p} M_q \left[ q^\uparrow(p) - q^\downarrow(p) \right] = \langle M_q \rangle \Delta q_L,
\]

(4)

with

\[
M_q = \left[ \left( p_0 + p_3 + m \right)^2 - \vec{p}_\perp^2 \right] \left/ [2(p_0 + p_3)(m + p_0)] \right.
\]

(5)

being the contribution from the relativistic effect due to the quark transversal motions, \(q^\uparrow(p)\) and \(q^\downarrow(p)\) being the probabilities of finding, in the proton rest frame, a quark or antiquark of flavor \(q\) with rest mass \(m\) and momentum \(p_\mu\) and with spin parallel or antiparallel to the proton spin respectively, and \(\Delta q_L = \int d^3\vec{p} [q^\uparrow(p) - q^\downarrow(p)]\) being the net spin vector sum of quark flavor \(q\) parallel to the proton spin in the rest frame. Thus one sees that the quantity \(\Delta q\) should be interpreted as the net spin polarization in the infinite momentum
frame if one properly considers the relativistic effect due to internal quark transversal motions.

Since \(<M_q>\), the average contribution from the relativistic effect due to internal transversal motions of quark flavor \(q\), ranges from 0 to 1 (or more properly, it should be around 0.75 for light flavor quarks and approaches 1 for heavy flavor quarks), and \(\Delta q_L\), the net spin vector polarization of quark flavor \(q\) parallel to the proton spin in the proton rest frame, is related to the quantity \(\Delta q\) by the relation \(\Delta q_L = \Delta q/ <M_q>\), we have sufficient freedom to make the naive quark model spin sum rule, i.e., \(\Delta u_L + \Delta d_L + \Delta s_L = 1\), satisfied while still preserving the values of \(\Delta u\), \(\Delta d\) and \(\Delta s\) as parametrized from experimental data in appropriate explanations. Thereby we can understand the “spin crisis” simply because the quantity \(\Delta \Sigma = \Delta u + \Delta d + \Delta s\) does not represent, in a strict sense, the vector sum of the spin carried by the quarks in the naive quark model. It is possible that the value of \(\Delta \Sigma = \Delta u + \Delta d + \Delta s\) is small whereas the spin sum rule

\[
\Delta u_L + \Delta d_L + \Delta s_L = 1
\]

for the naive quark model still holds, though the realistic situation may be complicated.

2 A Light-Cone Quark-Spectator-Diquark Model for Nucleons

From the impulse approximation picture of deep inelastic scattering, one can calculate the valence quark distributions in the quark-diquark model where the single valence quark is the scattered parton and the non-interacting diquark serves to provide the quantum number of the spectator. The proton wave function in the quark-diquark model is written as

\[
\Psi_p^{\uparrow\downarrow}(qD) = \sin \theta \varphi_V |qV>^{\uparrow\downarrow} + \cos \theta \varphi_S |qS>^{\uparrow\downarrow},
\]

with

\[
|qV>^{\uparrow\downarrow} = \pm \frac{1}{2} [V_0(ud)u^{\uparrow\downarrow} + \sqrt{2}V_{\pm1}(ud)u^{\uparrow\downarrow} - \sqrt{2}V_0(uu)d^{\uparrow\downarrow} + 2V_{\pm1}(uu)d^{\uparrow\downarrow}];
\]

\[
|qS>^{\uparrow\downarrow} = S(ud)u^{\uparrow\downarrow},
\]

where \(V_s(q_1q_2)\) stays for a \(q_1q_2\) vector diquark Fock state with third spin component \(s_z\), \(S(ud)\) stays for a \(ud\) scalar diquark Fock state, \(\varphi_D\) stays for the momentum space wave function of the quark-diquark with \(D\) representing the vector (\(V\)) or scalar (\(S\)) diquarks, and \(\theta\) is a mixing angle that breaks SU(6) symmetry at \(\theta \neq \pi/4\). We choose the bulk SU(6) symmetry case \(\theta = \pi/4\).
From Eq. (7) we get the unpolarized quark distributions

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

(9)

where \( a_D(x) \) \((D = S \text{ or } V)\) is normalized such that \( \int_0^1 dx a_D(x) = 3 \) and denotes the amplitude for the quark \( q \) is scattered while the spectator is in the diquark state \( D \). Therefore we can write, by assuming the isospin symmetry between the proton and the neutron, the unpolarized structure functions for nucleons,

\[ F^p_2(x) = xs(x) + \frac{2}{3}xas(x) + \frac{1}{3}xav(x); \]
\[ F^n_2(x) = xs(x) + \frac{1}{18}xas(x) + \frac{1}{6}xav(x), \]

(10)

where \( s(x) \) denotes the contribution from the sea.

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 \( F^p_2(x)/F^n_2(x) \geq 2/3 \) for all \( x \) and is ruled out by the experimental observation \( F^p_2(x)/F^n_2(x) < 1/2 \) for \( x \to 1 \). It has been a well established fact that the valence flavor symmetry \( u_v(x) = 2d_v(x) \) does not hold and the explicit \( u_v(x) \) and \( d_v(x) \) can be parameterized from the combined experimental data from deep inelastic scatterings of electron (muon) and neutrino (anti-neutrino) on the proton and the neutron et al.. In this sense, any theoretical calculation of quark distributions should reflect the flavor asymmetry between the valence \( u \) and \( d \) quarks in a reasonable picture. It has been shown that the mass difference between the scalar and vector spectators can reproduce the up and down valence quark asymmetry that accounts for the observed ratio \( F^p_2(x)/F^n_2(x) \) at large \( x \).

The amplitude for the quark \( q \) is scattered while the spectator in the spin state \( D \) can be written as

\[ a_D(x) \propto \int|d^2k_\perp|\varphi_D(x, k_\perp)|^2. \]

(11)

We adopt the Brodsky-Huang-Lepage prescription for the light-cone momentum space wave function \( \varphi_D \) of the quark-spectator

\[ \varphi_D(x, k_\perp) = A_D exp\{-\frac{1}{8\beta_D^2}\left[\frac{m_q^2 + k_\perp^2}{x} + \frac{m_D^2 + k_\perp^2}{1 - x}\right]\}, \]

(12)

where \( k_\perp \) is the internal quark transversal momentum, \( m_q \) and \( m_D \) are the masses for the quark \( q \) and spectator \( D \), and \( \beta_D \) is the harmonic oscillator scale parameter. The values of the parameters \( \beta_D, m_q \) and \( m_D \) can be adjusted by...
fitting the hadron properties such as the electromagnetic form factors, the mean charge radiiues, and the weak decay constants et al. in the relativistic light-cone quark model. We simply adopt $m_q = 330$ MeV and $\beta_D = 330$ MeV. The masses of the scalar and vector spectators should be different taking into account the spin force from color magnetism or alternatively from instantons. We choose, e.g., $m_S = 600$ MeV and $m_V = 900$ MeV as estimated to explain the N-$\Delta$ mass difference. The mass difference between the scalar and vector spectators causes difference between $a_S(x)$ and $a_V(x)$ and thus the flavor asymmetry between the valence quark distribution functions $u_v(x)$ and $d_v(x)$. The calculated results are in reasonable agreement with the experimental data and this supports the quark-spectator picture of deep inelastic scattering in which the difference between the scalar and vector spectators is important to reproduce the explicit SU(6) symmetry breaking while the bulk SU(6) symmetry of the quark model still holds.

For the polarized quark distributions, we take into account the contribution from the Wigner rotation. 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 proton rest frame, one finds,

$$\Delta q(x) = \int (d^2k_\perp) W_D(x, k_\perp) [q_{s_z=\frac{1}{2}}(x, k_\perp) - q_{s_z=-\frac{1}{2}}(x, k_\perp)], \quad (13)$$

with

$$W_D(x, k_\perp) = \frac{(k^+ + m)^2 - k_\perp^2}{(k^+ + m)^2 + k_\perp^2} \quad (14)$$

being the contribution from the relativistic effect due to the quark transversal motions, $q_{s_z=\frac{1}{2}}(x, k_\perp)$ and $q_{s_z=-\frac{1}{2}}(x, k_\perp)$ being the probability of finding a quark and antiquark with rest mass $m$ and with spin parallel and anti-parallel to the rest proton spin, and $k^+ = xM$ where $M = \frac{m^2 + k_\perp^2}{x(1-x)}$. The Wigner rotation factor $W_D(x, k_\perp)$ ranges from 0 to 1; thus $\Delta q$ measured in polarized deep inelastic scattering cannot be identified with the spin carried by each quark flavor in the proton rest frame.

From Eq. (13) we get the spin distribution probabilities in the quark-diquark model

$$u^\uparrow_V = \frac{1}{18}; \quad u^\downarrow_V = \frac{2}{18}; \quad d^\uparrow_V = \frac{2}{18}; \quad d^\downarrow_V = \frac{4}{18};$$
$$u^\uparrow_S = \frac{1}{2}; \quad u^\downarrow_S = 0; \quad d^\uparrow_S = 0; \quad d^\downarrow_S = 0. \quad (15)$$
Taking into account the Wigner rotation, we can write the quark helicity distributions for the $u$ and $d$ quarks

\[
\Delta u_v(x) = u^v_\uparrow(x) - u^\downarrow_\uparrow(x) = -\frac{1}{3}a_V(x)W_V(x) + \frac{1}{3}a_S(x)W_S(x); \\
\Delta d_v(x) = d^\uparrow_\downarrow(x) - d^\downarrow_\uparrow(x) = -\frac{1}{3}a_V(x)W_V(x),
\]

where $W_D(x)$ is the correction factor due the Wigner rotation. From Eq. (14), one gets

\[
a_S(x) = 2u_v(x) - d_v(x); \\
a_V(x) = 3d_v(x).
\]

Combining Eqs. (16) and (17) we have

\[
\Delta u_v(x) = [u_v(x) - \frac{1}{3}d_v(x)]W_S(x) - \frac{1}{3}d_v(x)W_V(x); \\
\Delta d_v(x) = -\frac{1}{3}d_v(x)W_V(x).
\]

Thus we arrive at simple relations between the polarized and unpolarized quark distributions for the valence $u$ and $d$ quarks. We can calculate the quark helicity distributions $\Delta u_v(x)$ and $\Delta d_v(x)$ from the unpolarized quark distributions $u_v(x)$ and $d_v(x)$ by relations (15), once the detailed $x$-dependent Wigner rotation factor $W_D(x)$ is known. On the other hand, we can also use relations (18) to study $W_S(x)$ and $W_V(x)$, once there are good quark distributions $u_v(x)$, $d_v(x)$, $\Delta u_v(x)$, and $\Delta d_v(x)$ from experiments. From another point of view, the relations (18) can be considered as the results of the conventional SU(6) quark model by explicitly taking into account the Wigner rotation effect and the flavor asymmetry introduced by the mass difference between the scalar and vector spectators, thus any evidence for the invalidity of Eq. (18) will be useful to reveal new physics beyond the SU(6) quark model.

We calculated the $x$-dependent Wigner rotation factor $W_D(x)$ in the light-cone SU(6) quark-spectator model and noticed slight asymmetry between $W_S(x)$ and $W_V(x)$. Considering only the valence quark contributions, we can write the spin-dependent structure functions $g_1^p(x)$ and $g_1^n(x)$ for the proton and the neutron by

\[
g_1^p(x) = \frac{1}{2} \left[ \frac{5}{3} \Delta u_v(x) + \frac{2}{3} \Delta d_v(x) \right] = \frac{1}{3} \left[ 4u_v(x) - 2d_v(x) \right]W_S(x) - d_v(x)W_V(x); \\
g_1^n(x) = \frac{1}{2} \left[ \frac{5}{3} \Delta u_v(x) + \frac{2}{3} \Delta d_v(x) \right] = \frac{1}{3} \left[ 2u_v(x) - d_v(x) \right]W_S(x) - 3d_v(x)W_V(x).
\]

We found that the calculated $A_N^p$ with Wigner rotation are in agreement with the experimental data, at least for $x \geq 0.1$. The large asymmetry between $W_S(x)$ and $W_V(x)$ has consequence for a better fit of the data.

As we consider only the valence quark contributions to $g_1^p(x)$ and $g_1^n(x)$, we should not expect to fit the Ellis-Jaffe sum data from experiments. This
leaves room for additional contributions from sea quarks or other sources. We point out, however, it is possible to reproduce the observed Ellis-Jaffe sums $\Gamma_p^1 = \int_0^1 g^1_p(x) dx$ and $\Gamma_n^1 = \int_0^1 g^1_n(x) dx$ within the light-cone SU(6) quark-spectator model by introducing a large asymmetry between the Wigner rotation factors $W_S$ and $W_V$ for the scalar and vector spectators. For example, we need $< W_S > = 0.56$ and $< W_V > = 0.92$ to produce $\Gamma_p^1 = 0.136$ and $\Gamma_n^1 = -0.03$ as observed in experiments. This can be achieved by adopting a large difference between $\beta_S$ and $\beta_V$ which should be adjusted by fitting other nucleon properties in the model. The calculated $A_p^1(x)$, $A_n^1(x)$, and $A_d^1(x)$ are in good agreement with the data. This may suggest that the explicit SU(6) asymmetry could be also used to explain the EJSR violation (or partially) within a bulk SU(6) symmetry scheme of the quark model, or we take this as a hint for other SU(6) breaking source in additional to the SU(6) quark model.

We showed in the above that the $u$ and $d$ asymmetry in the lowest valence component of the nucleon and the Wigner rotation effect due to the internal quark transversal motions are important for re-producing the observed ratio $F_n^2/F_p^2$ and the polarization asymmetries $A_N^1$ for the proton, neutron, and deuteron. For a better understanding of the origin of polarized sea quarks implied by the violation of the Ellis-Jaffe sum rule, we still need to consider the higher Fock states implied by the non-perturbative meson-baryon fluctuations.

In the light-cone meson-baryon fluctuation model, the net $d$ quark helicity of the intrinsic $q\bar{q}$ fluctuation is negative, whereas the net $\bar{d}$ antiquark helicity is zero. Therefore the quark/antiquark asymmetry of the $d\bar{d}$ pairs should be apparent in the $d$ quark and antiquark helicity distributions. There are now explicit measurements of the helicity distributions for the individual $u$ and $d$ valence and sea quarks by SMC. The helicity distributions for the $u$ and $d$ antiquarks are consistent with zero in agreement with the results of the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs. The calculated quark helicity distributions $\Delta u_v(x)$ and $\Delta d_v(x)$ have been compared with the recent SMC data. The data are still not precise enough for making detailed comparison, but the agreement with $\Delta u_v(x)$ seems to be good. It seems that the agreement with $\Delta d_v(x)$ is poor and there is somewhat evidence for additional source of negative helicity contribution to the valence $d$ quark beyond the conventional quark model. This again supports the light-cone meson-baryon fluctuation model in which the helicity distribution of the intrinsic $d$ sea quarks $\Delta d_s(x)$ is negative.

The standard SU(6) quark model gives the constraints $|\Delta u_v| \leq \frac{\alpha}{3}$ and $|\Delta d_v| \leq \frac{\alpha}{3}$. A global fit of polarized deep inelastic scattering data together with constraints from nucleon and hyperon decay and the included higher-order perturbative QCD corrections leads to values for different quark helicity
contributions in the proton: \( \Delta u = 0.83 \pm 0.03, \quad \Delta d = -0.43 \pm 0.03, \quad \Delta s = -0.10 \pm 0.03 \). In the light-cone meson-baryon fluctuation model, the antiquark helicity contributions are zero. We thus can consider the empirical values as the helicity contributions \( \Delta q = \Delta q_v + \Delta q_s \) from both the valence \( q_v \) and sea \( q_s \) quarks. Thus the empirical result \(|\Delta d| > \frac{1}{3}\) strongly implies an additional negative contribution \( \Delta d_s \) in the nucleon sea.

3 The Meson-Baryon Fluctuations of the Nucleon Sea

The light-cone meson-baryon fluctuation model of intrinsic \( q\bar{q} \) pairs leads to a consistent picture for understanding a number of empirical anomalies related to the composition of the nucleons in terms of their non-valence sea quarks. We have studied the sea quark/antiquark asymmetries in the nucleon wavefunction which are generated by a light-cone model of energetically-favored meson-baryon fluctuations. The model predicts striking quark/antiquark asymmetries in the momentum and helicity distributions for the down and strange contributions to the proton structure function: the intrinsic \( d \) and \( s \) quarks in the proton sea are negatively polarized, whereas the intrinsic \( \bar{d} \) and \( \bar{s} \) antiquarks give zero contributions to the proton spin. Such a picture is supported by experimental phenomena related to the proton spin problem: the recent SMC measurement of helicity distributions for the individual up and down valence quarks and sea antiquarks, the global fit of different quark helicity contributions from experimental data, and the negative strange quark helicity from the \( \Lambda \) polarization in \( \bar{v}N \) experiments by the WA59 Collaboration. The light-cone meson-baryon fluctuation model also suggests a structured momentum distribution asymmetry for strange quarks and antiquarks which is related to an outstanding conflict between two different measures of strange quark sea in the nucleon. The model predicts an excess of intrinsic \( d\bar{d} \) pairs over \( u\bar{u} \) pairs, as supported by the Gottfried sum rule violation. We also predict that the intrinsic charm and anticharm helicity and momentum distributions are not identical.

The intrinsic sea model thus gives a clear picture of quark flavor and helicity distributions supported qualitatively by a number of experimental phenomena. It seems to be an important physical source for the problems of the Gottfried sum rule violation, the Ellis-Jaffe sum rule violation, and the conflict between two different measures of strange quark distributions.
4 Conclusion

The “intrinsic” $q\bar{q}$ pairs generated by the non-perturbative meson-baryon fluctuations in the nucleon sea are an important source for a consistent picture of a number of empirical anomalies. The violations of the Gottfried sum rule and the Ellis-Jaffe sum rule are closely connected by the meson-baryon fluctuations in the nucleon, in contrary to most studies in which they are not related. The violation of the Ellis-Jaffe sum rule does not in conflict with the SU(6) quark model, provided that the relativistic effect from the Wigner rotation, the flavor asymmetry generated by the spin-spin interactions of the valence quarks, and the intrinsic $q\bar{q}$ pairs generated by non-perturbative meson-baryon fluctuations are taken into account. One important prediction of the model is the significant quark/antiquark asymmetries in the momentum and helicity distributions for the quarks and antiquarks of the nucleon sea, contrary to intuition based on perturbative gluon-splitting processes. It is important to test the meson-baryon fluctuation model by it’s predictions in various physical processes, such as the forward energetic neutron events at HERA and the asymmetric quark/antiquark hadronization in $e^+e^-$ annihilation.

Acknowledgments

I am very grateful to Professors Stan J. Brodsky, Tao Huang, and Qi-Ren Zhang for their valuable contribution, guidance and encouragement during the profitable and enjoyable collaborations from which the contents in this talk were developed.

References

1. For a recent review, see, e.g., M. Anselmino, A. Efremov, and E. Leader, Phys. Rep. 261 (1995) 1.
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. S. J. Brodsky and B.-Q. Ma, Phys. Lett. B 381 (1996) 317.
6. B.-Q. Ma, Z. Phys. A 345 (1993) (321).
7. T. Huang, B.-Q. Ma, and Q.-X. Shen, Phys. Rev. D 49 (1994) 1490.
8. B.-Q. Ma and T. Huang, J. Phys. G 21 (1995) 765.
9. M. I. Pavković, Phys. Rev. D 13 (1976) 2128.
10. J. Kuti and V. F. Weisskopf, Phys. Rev. 4 (1971) 3419.
11. S. J. Brodsky, T. Huang, and G. P. Lepage, in: *Particles and Fields*, eds. A. Z. Capri and A. N. Kamal (Plenum, New York, 1983), p. 143.
12. H. J. Weber, Phys. Lett. B 287 (1992) 14; Phys. Rev. D 49 (1994) 3160.
13. SM Collab., B. Adeva *et al.*, Phys. Lett. B 369 (1996) 93.
14. J. Ellis and M. Karliner, Phys. Lett. B 341 (1995) 397.
15. B.-Q. Ma, Chin. Phys. Lett. 13 (1996) 648 [hep-ph/9604342].
16. See, e.g., B.-Q. Ma, A. Schäfer and W. Greiner, Phys. Rev. D 47 (1993) 51, and references therein.
17. S.J. Brodsky and B.-Q. Ma, Phys. Lett. B 392 (1997) 452 [hep-ph/9610304].