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The Spin and Flavor Content of Intrinsic Sea Quarks[a]

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Abstract

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1 Introduction

By far the most unexpected empirical features of the structure of hadrons relate to the composition of the nucleons in terms of their nonvalence quarks. For example, the violation of the Gottfried sum rule measured by the New Muon Collaboration (NMC) indicates a strong violation of SU(2) symmetry in the $\bar{u}$ and $\bar{d}$ distributions [1]. The large violation of the Ellis-Jaffe sum rule as observed at CERN and SLAC indicates that only a small fraction of the proton's helicity is provided by quarks [2]. The European Muon Collaboration (EMC) has observed a large excess of charm quarks at large momentum fraction x in comparison with the charm distributions predicted from photon-gluon fusion processes[3]. Furthermore, as we have recently emphasized[4], it is not even clear that the quark and antiquark sea distributions have identical momentum and helicity distributions, contrary to intuition based on perturbative gluon-splitting processes.

It is important to distinguish two distinct types of quark and gluon contributions to the nucleon sea measured in deep inelastic scattering: "extrinsic" and "intrinsic". We shall refer to the sea quarks generated from the QCD hard bremsstrahlung and gluon-splitting as "extrinsic" quarks, since the sea quark structure is associated with the internal composition of gluons, rather than the proton itself. In contrast, sea quarks which are multi-connected to the valence quarks of the nucleon are referred to as "intrinsic" sea quarks [4,5]. In this talk we shall show that the intrinsic quark-antiquark pairs generated by the minimal energy nonperturbative meson-baryon fluctuations in the nucleon sea provide a consistent framework for understanding the origin of polarized light-flavor and strange sea quarks implied by the violation of the Ellis-Jaffe sum rule. Furthermore, the meson-baryon fluctuations of the nucleon sea cause 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 predicted to be negatively polarized, whereas the intrinsic $\bar{d}$ and $\bar{s}$ antiquarks give zero contributions to the proton spin. The momentum distribution asymmetry for strange quarks and antiquarks is supported by an outstanding conflict between two different determinations of the 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.

In Fock state wavefunctions containing heavy quarks, the minimal energy configuration occurs when the constituents have similar rapidities. Thus one of the most natural features of intrinsic heavy sea quarks is their contribution to the nucleon structure functions at large x in contrast to the small x heavy quark distributions predicted from photon-gluon fusion processes. This feature of intrinsic charm is supported by the EMC observation of a large excess of charm quarks at large x [3,5,6].

2 The meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs

The intrinsic sea quarks and gluons are multi-connected to the valence quarks and exist over a relatively long lifetime within the nucleon bound state. Thus the intrinsic $q\bar{q}$ pairs can arrange themselves together with the valence quarks of the target nucleon into the most energetically-favored meson-baryon fluctuations. For example, the coupling of a proton to a virtual $K^+\Lambda$ pair provides a specific source of intrinsic strange quarks and antiquarks in the proton. Since the s and $\bar{s}$ quarks appear in different configurations in the lowest-lying hadronic pair states, their helicity and momentum distributions are distinct. In our analysis, we have utilized [4] a boost-invariant light-cone Fock state description of the hadron wavefunction which emphasizes multi-parton configurations of minimal invariant mass.

In order to characterize the momentum and helicity distributions of intrinsic $q\bar{q}$ pairs, we adopt a light-cone two-level convolution model of structure functions [7] in which the nucleon is a two-body system of meson and baryon which are also composite systems of quarks and gluons. 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 K^+ meson is a pseudoscalar particle with negative parity, and the Λ baryon has the same parity of the nucleon. We thus write the total angular momentum space wavefunction of the intermediate $K\Lambda$ state in the center-of-mass reference frame as

$$\begin{aligned} \left| J=\frac{1}{2}, J_z=\frac{1}{2} \right\rangle &= \sqrt{\frac{2}{3}} \left| L=1, L_z=1 \right\rangle \left| S=\frac{1}{2}, S_z=-\frac{1}{2} \right\rangle \\ &- \sqrt{\frac{1}{3}} \left| L=1, L_z=0 \right\rangle \left| S=\frac{1}{2}, S_z=\frac{1}{2} \right\rangle . \end{aligned} \quad (1)$$

Thus 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: $\Delta S_{\bar{s}} = 0$. There thus can be a significant quark and antiquark asymmetry in the quark spin distributions for the intrinsic $s\bar{s}$ pairs.

The quark helicity projections measured in deep inelastic scattering are related to the quark spin projections in the target rest frame by multiplying by a Wigner rotation factor of order 0.75 for light quarks and of order 1 for heavy quarks[8]. We therefore predict that the net strange quark helicity arising from the intrinsic $s\bar{s}$ pairs in the nucleon wavefunction is negative, whereas the net antistrange quark helicity is approximately zero.

The momentum distributions of the intrinsic strange and antistrange quarks in the $K^+\Lambda$ state can be modeled from the two-level convolution formula

$$s(x) = \int_x^1 \frac{\mathrm{d}y}{y} f_{\Lambda/K^+\Lambda}(y) q_{s/\Lambda}\left(\frac{x}{y}\right) ; \; \bar{s}(x) = \int_x^1 \frac{\mathrm{d}y}{y} f_{K^+/K^+\Lambda}(y) q_{\bar{s}/K^+}\left(\frac{x}{y}\right) , \quad (2)$$

where $f_{\Lambda/K^+\Lambda}(y)$, $f_{K^+/K^+\Lambda}(y)$ are probability distributions of finding Λ, K^+ in the $K^+\Lambda$ state with the light-cone momentum fraction y and $q_{s/\Lambda}(x/y)$, $q_{\bar{s}/K^+}(x/y)$ are probability distributions of finding strange, antistrange quarks in Λ, K^+ with the light-cone momentum fraction x/y. We estimate these quantities by adopting two-body momentum wavefunctions for $p = K^+\Lambda$, $K^+ = u\bar{s}$, and $\Lambda = sud$ where the ud in Λ serves as a spectator in the quark-spectator model[9]. We calculated the momentum distributions $s(x)$, $\bar{s}(x)$, and $\delta_s(x) = s(x) - \bar{s}(x)$ and found a significant quark/antiquark asymmetry of the momentum distributions for the strange sea quarks[4], as shown in Fig. 1.

We have performed similar calculations for the momentum distributions of the intrinsic $d\bar{d}$ and $c\bar{c}$ pairs arising from the $p(uudd\bar{d}) = \pi^+(u\bar{d})n(udd)$ and $p(uudc\bar{c}) = \bar{D}^0(u\bar{c})\Lambda_c^+(udc)$ configurations. The $c\bar{c}$ momentum asymmetry is small compared with the $s\bar{s}$ and $d\bar{d}$ asymmetries but is still nontrivial. The $c\bar{c}$ spin asymmetry, however, is large. Considering that it is difficult to observe

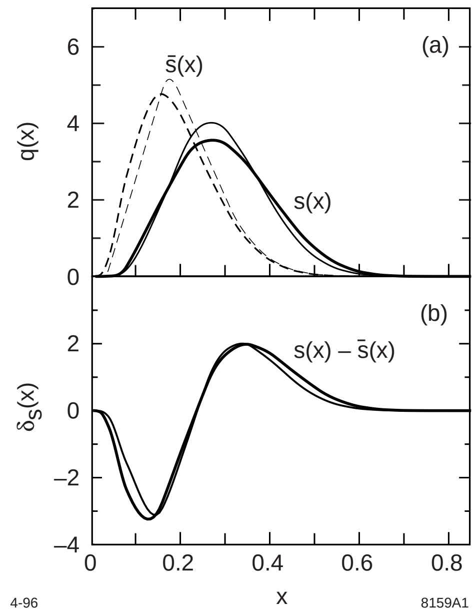

Figure 1: The momentum distributions for the strange quarks and antiquarks in the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs, with the fluctuation wavefunction of $K^+\Lambda$ normalized to 1. The curves in (a) are the calculated results of $s(x)$ (solid curves) and $\bar{s}(x)$ (broken curves) with the Gaussian type (thick curves) and power-law type (thin curves) wavefunctions and the curves in (b) are the corresponding $\delta_s(x) = s(x) - \bar{s}(x)$.

the momentum asymmetry for the $d\bar{d}$ pairs due to an additional valence d quark in the proton, the momentum asymmetry of the intrinsic strange and antistrange quarks is the most significant feature of the model and the easiest to observe.

3 The light-flavor sea quark content and the Gottfried sum rule violation

Parton sum rules provide information on the quark distributions in nucleons and thus allow for sensitive investigations of the detailed flavor and spin content of nucleons. The Gottfried sum rule (GSR) violation reported by the New Muon Collaboration (NMC) [10] has inspired a number of discussions on the flavor dependence of sea distributions in the nucleons. The Gottfried sum is expressed as

$$S_G = \int_0^1 [F_2^p(x_B) - F_2^n(x_B)] \frac{\mathrm{d}x_B}{x_B} = \frac{1}{3} + \int_0^1 \sum_i [2\overline{q}_i^p(x_B) - 2\overline{q}_i^n(x_B)]\, \mathrm{d}x_B. \quad (3)$$

Under the assumptions of isospin symmetry between proton and neutron, and flavor symmetry in the sea, one arrives at the Gottfried sum rule (GSR), $S_G = 1/3$. However, the value of S_G measured in the NMC experiment is

$$S_G = 0.235 \pm 0.026, \quad (4)$$

which is significantly smaller than the simple quark-parton-model result of 1/3. Several different explanations for the origin of the GSR violation have been proposed, such as flavor asymmetry of the nucleon sea [11,12], isospin symmetry breaking between the proton and the neutron [13] *et al.*. Among the various explanations, the most natural one is the u and d flavor asymmetry of the nucleon sea which is implied by the meson cloud of the nucleon [12].

The light-cone meson-baryon fluctuation model contains neutral meson fluctuation configurations in which the intermediate mesons are composite systems of the intrinsic up $u\bar{u}$ and down $d\bar{d}$ pairs, but these fluctuations do not cause a flavor asymmetry in the nucleon sea. 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 $\pi^+(u\bar{d})n(udd)$. This leads naturally to an excess of $d\bar{d}$ pairs over $u\bar{u}$ pairs in the proton sea. Such a mechanism provides a natural explanation [12] for the violation of the Gottfried sum rule [10] and leads to nontrivial distributions of the sea quarks. The NMC measurement $S_G = \frac{1}{3} + \frac{2}{3}\int_0^1 \mathrm{d}x[u_s(x) - d_s(x)] = 0.235 \pm 0.026$ [10] implies $\int_0^1 \mathrm{d}x[d_s(x) - u_s(x)] = 0.148 \pm 0.039$, which can be considered as the probability of finding nonneutral intrinsic $d\bar{d}$ fluctuations in the proton sea.

Thus, as a first support, the meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs provides a natural mechanism for the $u\bar{u}$ and $d\bar{d}$ asymmetry in the nucleon sea which is responsible for the most part of the Gottfried sum rule violation.

4 The spin content of the nucleon and the Ellis-Jaffe sum rule violation

The observation of the Ellis-Jaffe sum rule (EJSR) violation in the inclusive polarized deep inelastic scattering experiments has received an extensive attention on the spin content of nucleons. The experimental data of the integrated spin-dependent structure functions for the nucleons are generally understood to imply that the sum of the up, down, and strange quark helicities in the nucleon is much smaller than the nucleon spin. There has been a number of possible interpretations for the EJSR violation, and the quark helicity distributions for each flavor are quite different in these interpretations [2]. In most interpretations the Ellis-Jaffe sum rule violation is considered to be independent of the Gottfried sum rule violations. However, there have been speculations and suggestions about the interrelation between the two sum rule violations. It has been known [4] that the intrinsic $q\bar{q}$ pairs generated by the nonperturbative meson-baryon fluctuations in the nucleon sea, combined with the flavor asymmetry in the valence component of the nucleon [9] and the Wigner rotation effect due to the quark relativistic transversal motions [8], could provide a comprehensive picture to understand a number of phenomena related to the proton spin problem caused by the Ellis-Jaffe sum rule violation.

The unpolarized valence quark distributions $u_v(x)$ and $d_v(x)$ in the SU(6) quark-spectator model [9] are expressed by

$$\begin{array}{c} u_v(x) = \frac{1}{2}a_S(x) + \frac{1}{6}a_V(x); \\ d_v(x) = \frac{1}{3}a_V(x), \end{array} \tag{5}$$

where $a_D(x)$ ($D = S$ for scalar spectator or V for vector spectator) 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. 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 up and down valence quark asymmetry that accounts for the observed ratio $F_2^n(x)/F_2^p(x)$ at large x [9]. 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 to reproduce the explicit SU(6) symmetry breaking while the bulk SU(6) symmetry of the quark model still holds.

The quantity Δq measured in polarized deep inelastic scattering is defined by the axial current matrix element

$$\Delta q = < p, \uparrow | \overline{q} \gamma^+ \gamma_5 q | p, \uparrow > . \tag{6}$$

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 distributions 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,

$$\Delta q(x)=\int[\mathrm{d}^2\mathbf{k}_\perp]W_D(x,\mathbf{k}_\perp)[q_{s_z=\frac{1}{2}}(x,\mathbf{k}_\perp)-q_{s_z=-\frac{1}{2}}(x,\mathbf{k}_\perp)], \tag{7}$$

with

$$W_D(x,\mathbf{k}_\perp)=\frac{(k^+ + m)^2-\mathbf{k}_\perp^2}{(k^+ + m)^2+\mathbf{k}_\perp^2} \tag{8}$$

being the contribution from the relativistic effect due to the quark transversal motions [8], $q_{s_z=\frac{1}{2}}(x,\mathbf{k}_\perp)$ and $q_{s_z=-\frac{1}{2}}(x,\mathbf{k}_\perp)$ being the probability distributions of finding a quark and antiquark with rest mass m and with spin parallel and anti-parallel to the rest proton spin, and $k^+=x\mathcal{M}$ where $\mathcal{M}=\frac{m_q^2+\mathbf{k}_\perp^2}{x}+\frac{m_D^2+\mathbf{k}_\perp^2}{1-x}$. The Wigner rotation factor $W_D(x,\mathbf{k}_\perp)$ ranges from 0 to 1; thus Δq measured in polarized deep inelastic scattering cannot be identified with the spin carried by each quark flavor in the proton rest frame [8].

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

$$\begin{aligned}\Delta u_v(x)=u_v^{\uparrow}(x)-u_v^{\downarrow}(x)=-\tfrac{1}{18}a_V(x)W_V(x)+\tfrac{1}{2}a_S(x)W_S(x);\\ \Delta d_v(x)=d_v^{\uparrow}(x)-d_v^{\downarrow}(x)=-\tfrac{1}{9}a_V(x)W_V(x).\end{aligned} \tag{9}$$

From Eq. (5) one gets

$$\begin{aligned}a_S(x)=2u_v(x)-d_v(x);\\ a_V(x)=3d_v(x).\end{aligned} \tag{10}$$

Combining Eqs. (9) and (10) we have

$$\begin{aligned}\Delta u_v(x)=[u_v(x)-\tfrac{1}{2}d_v(x)]W_S(x)-\tfrac{1}{6}d_v(x)W_V(x);\\ \Delta d_v(x)=-\tfrac{1}{3}d_v(x)W_V(x).\end{aligned} \tag{11}$$

Thus we arrive at simple relations [9] between the polarized and unpolarized quark distributions for the valence u and d quarks. The relations (11) can be considered as the results of the conventional SU(6) quark model by explicitly taking into account the Wigner rotation effect [8] and the flavor asymmetry introduced by the mass difference between the scalar and vector spectators [9]; thus any evidence for the invalidity of Eq. (11) will be useful for revealing new physics beyond the SU(6) quark model.

The x-dependent Wigner rotation factor $W_D(x)$ has been calculated in the light-cone SU(6) quark-spectator model [9] and an asymmetry between $W_S(x)$

and $W_V(x)$ was observed. The calculated polarization asymmetries $A_1^N = 2xg_1^N(x)/F_2^N(x)$ including the Wigner rotation have been found [9] to be in agreement with the experimental data, at least for $x \geq 0.1$. A large asymmetry between $W_S(x)$ and $W_V(x)$ leads to a better fit to the data.

Thus 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 both important for reproducing the observed ratio F_2^n/F_2^p and the proton, neutron, and deuteron polarization asymmetries, A_1^p, A_1^n, A_1^d. For a better understanding of the origin of polarized sea quarks implied by the violation of the Ellis-Jaffe sum rule [14], we still need to consider the higher Fock states implied by the nonperturbative 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 the Spin Muon Collaboration (SMC) [15]. 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 data for the quark helicity distributions $\Delta u_v(x)$ and $\Delta d_v(x)$ are still not precise enough for making detailed comparison, but the agreement with $\Delta u_v(x)$ seems to be good. 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. 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.

5 The strange quark/antiquark asymmetry in the nucleon sea

We have shown that the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs leads to significant quark/antiquark asymmetries in the momentum and helicity distributions of the nucleon sea quarks. There is still no direct experimental confirmation of the strange/antistrange asymmetry, although there have been suggestions from estimates in the cloudy bag model [16] and Skyrme solutions to chiral theories [17]. However, there are difficulties in understanding the discrepancy between two different determinations of the strange quark content in the nucleon sea [18,19,20] assuming conventional considerations [21] and perturbative QCD effects [22]. It has been shown that a strange/antistrange momentum asymmetry in the nucleon can be inferred from the apparent strange conflict [4], as can be seen from Fig. 2.

Although the quark/antiquark asymmetries for the intrinsic $q\bar{q}$ pairs can

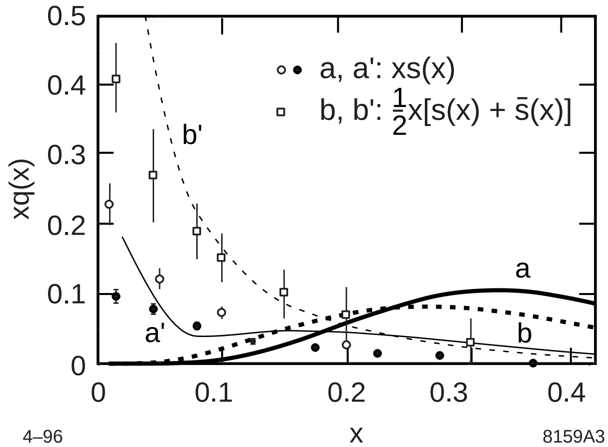

Figure 2: Results for the strange quark distributions $xs(x)$ and $x\bar{s}(x)$ as a function of the Bjorken scaling variable x. The open squares shows the CTEQ determination[18] of $\frac{1}{2}x[s(x)+\bar{s}(x)]$ obtained from $\frac{5}{12}(F_2^{\nu\mathcal{N}}+F_2^{\overline{\nu}\mathcal{N}})(x)(\mathrm{CCFR})-3F_2^{\mu\mathcal{N}}(x)(\mathrm{NMC})$. The circles show the CCFR determinations for $xs(x)$ from dimuon events in neutrino scattering using a leading-order QCD analysis at $Q^2\approx 5(\mathrm{GeV/c})^2$ (closed circles)[19] and a higher-order QCD analysis at $Q^2=20(\mathrm{GeV/c})^2$ (open circles)[20]. The thick curves are the unevolved predictions of the light-cone fluctuation model for $xs(x)$ (solid curve labeled a) and $\frac{1}{2}x[s(x)+\bar{s}(x)]$ (broken curve labeled b) for the Gaussian type wavefunction in the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs assuming a probability of 10% for the $K^+\Lambda$ state. The thin solid and broken curves (labeled a' and b') are the corresponding evolved predictions multiplied by $d_v(x)|_{fit}/d_v(x)|_{model}$ assuming a probability of 4% for the $K^+\Lambda$ state.

explain the above conflict between two different determinations of the strange quark sea in the nucleon[4], there is still no direct experimental confirmation for such asymmetries. If there are significant quark/antiquark asymmetries in the distribution of the $s\bar{s}$ pairs in the nucleon sea, corresponding asymmetries should appear in the jet fragmentation of s versus $\bar{s}$ quarks into nucleons. For example, if one can identify a pure sample of tagged s jets, then one could look at the difference of $D_{p/s}(z)-D_{\bar{p}/s}(z)$ at large z, where $D_{h/q}(z)$ is the fragmentation function representing the probability distribution for the fragmentation of the quark q into hadron h and z is the fraction of the quark momentum carried by the fragmented hadron. It has been shown[23] that the hadronic jet fragmentation of the s and c quarks in electron-positron (e^+e^-) annihilation may provide a feasible laboratory for identifying quark/antiquark asymmetries in the nucleon sea.

The strange quark-antiquark asymmetry implies a nonzero strangeness contribution to the magnetic moment of the nucleon. The predictions of the meson-baryon fluctuation model and the uncertainties due to isospin symmetry breaking between the proton and neutron for the experimental extraction of the strangeness contribution to nucleon moments are discussed in ref. [24].

6 Summary

Intrinsic sea quarks clearly play a key role in determining basic properties of the nucleon. As we have shown above, the corresponding intrinsic contributions to the sea quark structure functions lead to nontrivial, asymmetric, and structured momentum and spin distributions. We have studied the intrinsic sea quarks in the nucleon wavefunction which are generated by a light-cone model of energetically-favored meson-baryon fluctuations. Such a model 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, and the global fit of different quark helicity contributions from experimental data *et al.* 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, which is supported qualitatively by a number of experimental phenomena. It seems to be an important physical source for the violation of the Gottfried and Ellis-Jaffe sum rules and the conflict between two different measures of strange quark distributions.

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