

SLAC-PUB-7126

BIHEP-TH-96-13

The Quark/Antiquark Asymmetry of the Nucleon Sea *

Stanley J. Brodsky

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309, USA
e-mail: sjbth@slac.stanford.edu

Bo-Qiang Ma

CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China
Institute of High Energy Physics, Academia Sinica
P. O. Box 918(4), Beijing 100039, China
and
Faculty of Natural Sciences, Kwanghua Academy of Sciences
Beijing 100081, China
e-mail: mabq@bepc3.ihep.ac.cn

Submitted to Physics Letters B.

*Work partially supported by the Department of Energy, contract DE-AC03-76SF00515 and by National Natural Science Foundation of China under Grant No. 19445004 and National Education Committee of China under Grant No. JWSL[1995]806.

Abstract

Although the distributions of sea quarks and antiquarks generated by leading-twist QCD evolution through gluon splitting $g \rightarrow \bar{q}q$ are necessarily CP symmetric, the distributions of nonvalence quarks and antiquarks which are intrinsic to the nucleon's bound state wavefunction need not be identical. In this paper we investigate 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 predicted to be 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 and the violation of the Ellis-Jaffe sum rule. The light-cone meson-baryon fluctuation model also suggests a structured momentum distribution asymmetry for strange quarks and antiquarks which could be relevant to 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. We also predict that the intrinsic charm and anticharm helicity and momentum distributions are not identical.

PACS numbers: 13.60.Hb, 11.30.Hv, 12.39.Ki, 13.88.+e

1 Introduction

The composition of the nucleon in terms of its fundamental quark and gluon degrees of freedom is a key focus of QCD phenomenology. In the light-cone (LC) Fock state description of bound states, each hadronic eigenstate of the QCD Hamiltonian is expanded at fixed light-cone time $\tau = t+z/c$ on the complete set of color-singlet eigenstates $\{|n\rangle\}$ of the free Hamiltonian which have the same global quantum numbers: $|p\rangle = \sum_n \psi_n^H(x_i, k_{\perp i}, \lambda_i) |n\rangle$. Thus each Fock component in the light-cone wavefunction of a nucleon is composed of three valence quarks, which gives the nucleon its global quantum numbers, plus a variable number of sea quark-antiquark ($q\bar{q}$) pairs of any flavor, plus any number of gluons. The quark distributions $q(x, \tilde{Q})$ of the nucleon measured in deep inelastic scattering are computed from the sum of squares of the light-cone wavefunctions integrated over transverse momentum k_{\perp} up to the factorization scale \tilde{Q} , where the light-cone momentum fraction $x = \frac{k^+}{p^+} = \frac{k^0+k^3}{P^0+P^3}$ of the struck quark is set equal to the Bjorken variable x_{BJ} .

It is important to distinguish two distinct types of quark and gluon contributions to the nucleon sea measured in deep inelastic lepton-nucleon scattering: “extrinsic” and “intrinsic” [1, 2, 3]. The extrinsic sea quarks and gluons are created as part of the lepton-scattering interaction and thus exist over a very short time $\Delta\tau \sim 1/Q$. These factorizable contributions can be systematically derived from the QCD hard bremsstrahlung and pair-production (gluon-splitting) subprocesses characteristic of leading twist perturbative QCD evolution. In contrast, the intrinsic sea quarks and gluons are multiconnected 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.

In conventional studies of the “sea” quark distributions, it is usually assumed that, aside from the effects due to antisymmetrization, the quark and antiquark sea contributions have the same momentum and helicity distributions. However, the ansatz of identical quark and antiquark sea contributions has never been justified, either theoretically or empirically. Obviously the sea distributions which arise directly from

gluon splitting in leading twist are necessarily CP-invariant; *i.e.*, they are symmetric under quark and antiquark interchange. However, the initial distributions which provide the boundary conditions for QCD evolution need not be symmetric since the nucleon state is itself not CP-invariant. Only the global quantum numbers of the nucleon must be conserved. The intrinsic sources of strange (and charm) quarks reflect the wavefunction structure of the bound state itself; accordingly, such distributions would not be expected to be CP symmetric. Thus the strange/antistrange asymmetry of nucleon structure functions provides a direct window into the quantum bound-state structure of hadronic wavefunctions.

It is also possible to consider the nucleon wavefunction at low resolution as a fluctuating system coupling to intermediate hadronic Fock states such as noninteracting meson-baryon pairs. The most important fluctuations are most likely to be those closest to the energy shell and thus have minimal invariant mass. 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.

The purpose of this paper is to investigate the quark and antiquark asymmetry in the nucleon sea which is implied by a light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs. Such fluctuations are necessarily part of any quantum-mechanical description of the hadronic bound state in QCD and have also been incorporated into the cloudy bag model [4] and Skyrme solutions to chiral theories [2]. We shall utilize a boost-invariant light-cone Fock state description of the hadron wavefunction which emphasizes multi-parton configurations of minimal invariant mass. We find that such fluctuations predict a striking sea quark and antiquark asymmetry in the corresponding momentum and helicity distributions in the nucleon structure functions. In particular, the strange and antistrange distributions in the nucleon generally have completely different momentum and spin characteristics. For example, the model predicts that the intrinsic d and s quarks in the proton sea are negatively polarized, whereas the intrinsic \bar{d} and \bar{s} antiquarks provide zero contributions to the proton spin. We also predict that the intrinsic charm and anticharm helicity and

momentum distributions are not strictly identical. We show that the above picture of quark and antiquark asymmetry in the momentum and helicity distributions of the nucleon sea quarks has support from a number of experimental observations, and we suggest processes to test and measure this quark and antiquark asymmetry in the nucleon sea.

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

In order to characterize the momentum and helicity distributions of intrinsic $q\bar{q}$ pairs, we shall adopt a light-cone two-level convolution model of structure functions [5] in which the nucleon is a two-body system of meson and baryon which are also composite systems of quarks and gluons. We first study the intrinsic strange $s\bar{s}$ pairs in the proton. In the meson-baryon fluctuation model, 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 [3]. The K^+ meson is a pseudoscalar particle with negative parity, and the Λ baryon has the same parity of the nucleon. The $K^+\Lambda$ state retains the parity of the proton, and consequently, the $K^+\Lambda$ system must have odd orbital angular momentum. We thus write the total angular momentum space wavefunction of the intermediate $K\Lambda$ state in the center-of-mass reference frame as

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

In the constituent quark model, the spin of Λ is provided by its strange quark and the net spin of the antistrange quark in K^+ is zero. The net spin projection of Λ in the $K^+\Lambda$ state is $S_z(\Lambda) = -\frac{1}{6}$. 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.

We also need to estimate the relative probabilities for other possible fluctuations with higher off-shell light-cone energy and invariant mass, such as $K^+(u\bar{s})\Sigma^0(uds)$, $K^0(d\bar{s})\Sigma^+(uus)$, and $K^{*+}(u\bar{s})\Lambda(uds)$. For example, we find that the relative probability of finding the $K^{*+}\Lambda$ configuration (which has positively-correlated strange quark spin) compared with $K^+\Lambda$ is 3.6% (8.9%) by using a same normalization constant for a light-cone Gaussian type (power-law type) wavefunction. We find that the higher fluctuations of intrinsic $s\bar{s}$ pairs do not alter the qualitative estimates of the quark and antiquark spin asymmetry in the nucleon sea based on using the $K^+\Lambda$ fluctuation alone.

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 [6]. 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. This aspect of quark/antiquark helicity asymmetry is in qualitative agreement with the predictions of a broken-U(3) version of the chiral quark model [7] where the intrinsic quark-antiquark pairs are introduced through quark to quark and Goldstone boson fluctuations.

In principle, one can measure the helicity distributions of strange quarks in the nucleon sea from the Λ longitudinal polarization of semi-inclusive Λ production in polarized deep inelastic scattering [3, 8, 9]. We expect that the polarization is negative for the produced Λ and zero (or slightly positive [2]) for the produced $\bar{\Lambda}$. The expectation of negative longitudinal Λ polarization is supported by the measurements of the WA59 Collaboration for the reaction $\bar{\nu} + N \rightarrow \mu^+ \Lambda + X$ [10]. The complementary measurement of $\bar{\Lambda}$ polarization in semi-inclusive deep inelastic scattering is clearly important in order to test the physical picture of the light-cone meson-baryon fluctuation model.

It is also interesting to study the sign of the Λ polarization in the current fragmentation region as the Bjorken variable $x \rightarrow 1$ in polarized proton deep inelastic

inclusive reactions. From perturbative QCD arguments on helicity retention, one expects a positive helicity distribution for any quark struck in the end-point region $x \rightarrow 1$, even though the global helicity correlation is negative [11]. Thus we predict that the sign of the Λ polarization should change from negative to positive as x approaches the endpoint regime.

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

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

where $f_{\Lambda/K^+\Lambda}(y)$, $f_{K^+/K^+\Lambda}(y)$ are probabilities 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 probabilities of finding strange, antistrange quarks in Λ , K^+ with the light-cone momentum fraction x/y . We shall 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 [12]. We choose two simple functions of the invariant mass $\mathcal{M}^2 = \sum_{i=1}^2 \frac{k_{\perp i}^2 + m_i^2}{x_i}$ for the two-body wavefunction: the Gaussian type and power-law type wavefunctions [13],

$$\psi_{\text{Gaussian}}(\mathcal{M}^2) = A_{\text{Gaussian}} \exp(-\mathcal{M}^2/2\alpha^2), \quad (3)$$

$$\psi_{\text{Power}}(\mathcal{M}^2) = A_{\text{Power}} (1 + \mathcal{M}^2/\alpha^2)^{-p}, \quad (4)$$

where α sets the characteristic internal momentum scale. We do not expect to produce realistic quark distributions with simple two-body wavefunctions; however, we can hope to explain some qualitative features of the data as well as relations between the different quark distributions [12]. The predictions for the momentum distributions $s(x)$, $\bar{s}(x)$, and $\delta_s(x) = s(x) - \bar{s}(x)$ are presented in Fig. 1. The strong, structured momentum asymmetry of the $s(x)$ and $\bar{s}(x)$ intrinsic distributions reflects the tendency of the wavefunction to minimize the relative velocities of the intermediate meson baryon state and is approximately same for the two wavefunctions.

We have performed similar calculations for the momentum distributions of the intrinsic $d\bar{d}$ and $c\bar{c}$ pairs arising from the $p(uud) = \pi^+(u\bar{d})n(udd)$ and $p(uud) =$

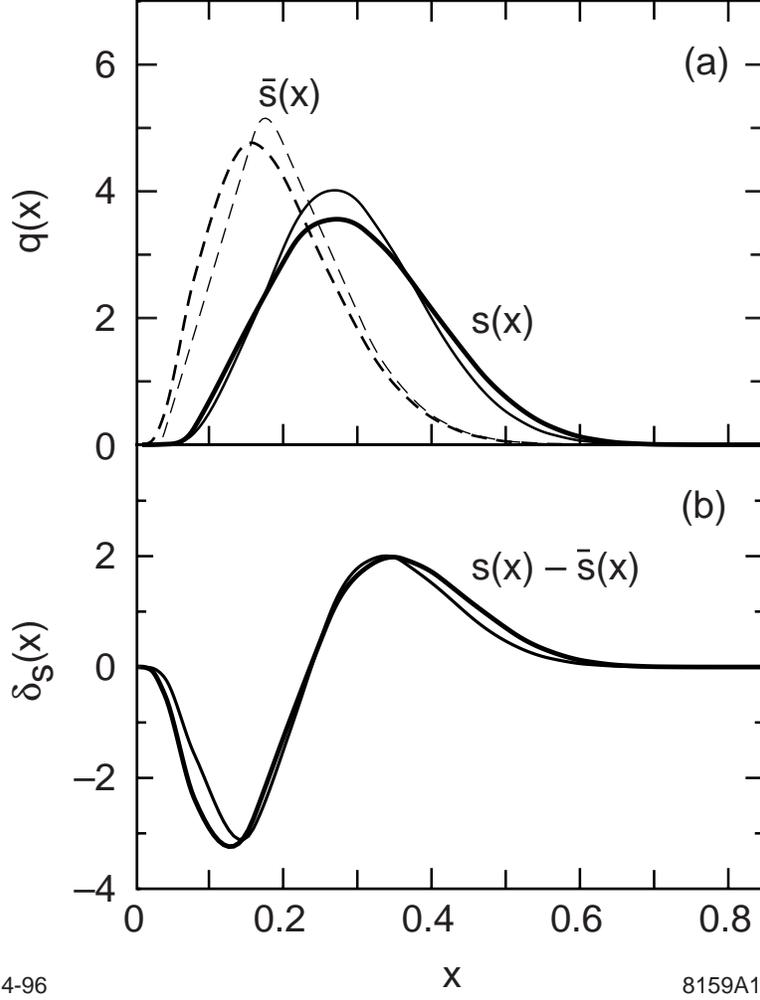


Figure 1: The momentum distributions for the strange quarks and antiquarks in the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs, with the fluctuation wavefunction of $K^+\Lambda$ normalized to 1. The curves in (a) are the calculated results of $s(x)$ (solid curves) and $\bar{s}(x)$ (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 parameters are $m_q = 330$ MeV for the light-flavor quark mass, $m_s = 480$ MeV for the strange quark mass, $m_D = 600$ MeV for the spectator mass, the universal momentum scale $\alpha = 330$ MeV, and the power constant $p = 3.5$, with realistic meson and baryon masses.

$\bar{D}^0(u\bar{c})\Lambda_c^+(udc)$ configurations. The results are presented in Fig. 2. We find a large quark and antiquark asymmetry for the $d\bar{d}$ pairs. 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 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. We have not taken into account the antisymmetrization effect of the u and d sea quarks with the valence quarks [14].

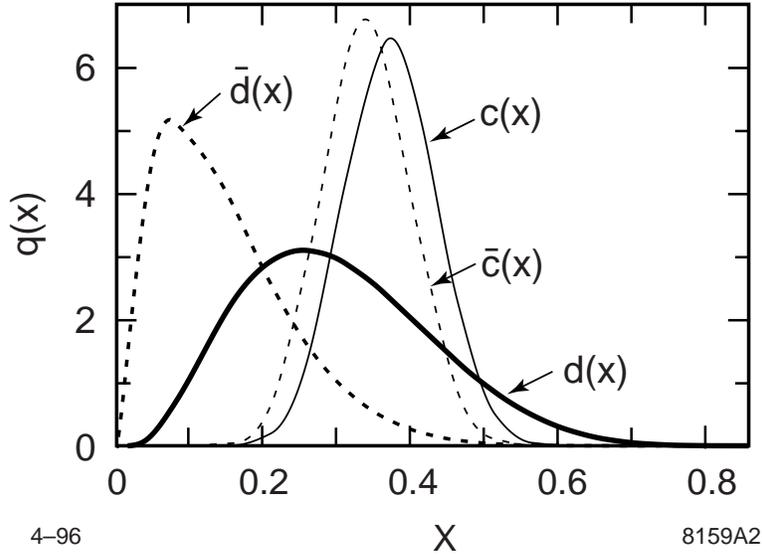


Figure 2: The momentum distributions for the down and charm quarks and anti-quarks in the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs, with the fluctuation wavefunctions normalized to 1. The curves are the calculated results for $d(x)$ (thick solid curve), $\bar{d}(x)$ (thick broken curve), $c(x)$ (thin solid curve), and $\bar{c}(x)$ (thin broken curve) with the Gaussian type wavefunction. The parameters are $m_d = 330$ MeV for the down quark mass and $m_c = 1500$ MeV for the charm quark mass, with other parameters as those in Fig. 1.

3 The strange quark/antiquark asymmetry in the nucleon sea

We have seen 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. A strange/antistrange asymmetry in the nucleon sea has also been suggested from estimates in the cloudy bag model [4] and Skyrme solutions to chiral theories [2]. At present there is still no direct experimental confirmation of the strange/antistrange asymmetry. However, a strange/antistrange momentum asymmetry in the nucleon can be inferred from the apparent conflict between two different determinations of the strange quark content in the nucleon sea.

The strange quark distribution in the nucleon is usually obtained from analyses of the deep inelastic lepton-nucleon scattering data assuming identical momentum distribution for the strange and antistrange quark distributions, *i.e.*, $s(x) = \bar{s}(x)$. The CTEQ [15] global analyses of quark distributions are based primarily on the following representations of the nucleon structure functions:

$$F_2^{\mu p} - F_2^{\mu n} = \frac{1}{3} x(u + \bar{u} - d - \bar{d}); \quad (5)$$

$$F_2^{\mu \mathcal{N}} = \frac{1}{2} (F_2^{\mu p} + F_2^{\mu n}) = \frac{5}{18} x \left[u + \bar{u} + d + \bar{d} + \frac{2}{5} (s + \bar{s}) \right]; \quad (6)$$

$$\frac{1}{2} (F_2^{\nu \mathcal{N}} + F_2^{\bar{\nu} \mathcal{N}}) = x(u + \bar{u} + d + \bar{d} + s + \bar{s}); \quad (7)$$

$$\frac{1}{2} (F_3^{\nu \mathcal{N}} + F_3^{\bar{\nu} \mathcal{N}}) = (u - \bar{u} + d - \bar{d} + s - \bar{s}), \quad (8)$$

where $F_{2,3}^{\mathcal{N}}$ are converted from $F_{2,3}^{F_e}$ using a heavy-target correction factor, with $F_{2,3}^{\mathcal{N}}$ denoting $\frac{1}{2}(F_{2,3}^p + F_{2,3}^n)$. These four observables determine four combinations of quark distributions, which can be taken to be $u + \bar{u}$, $d + \bar{d}$, $\bar{u} + \bar{d}$ and $s + \bar{s}$ if one neglects the relatively small contribution from the $s - \bar{s}$ term in Eq. (8). From Eqs. (6) and (7), one obtains the equality

$$\frac{5}{12} (F_2^{\nu \mathcal{N}} + F_2^{\bar{\nu} \mathcal{N}}) - 3F_2^{\mu \mathcal{N}} = \frac{1}{2} x[s(x) + \bar{s}(x)]. \quad (9)$$

The CTEQ Collaboration has determined the quantity on the left-hand side of Eq. (9) at $Q^2 = 5 \text{ GeV}^2$ using data from the New Muon Collaboration (NMC) [16] and CCFR

[17], as shown in Fig. 3. The strange quark distribution measured in this way can be effectively identified with the mean $\frac{1}{2}[s(x) + \bar{s}(x)]$.

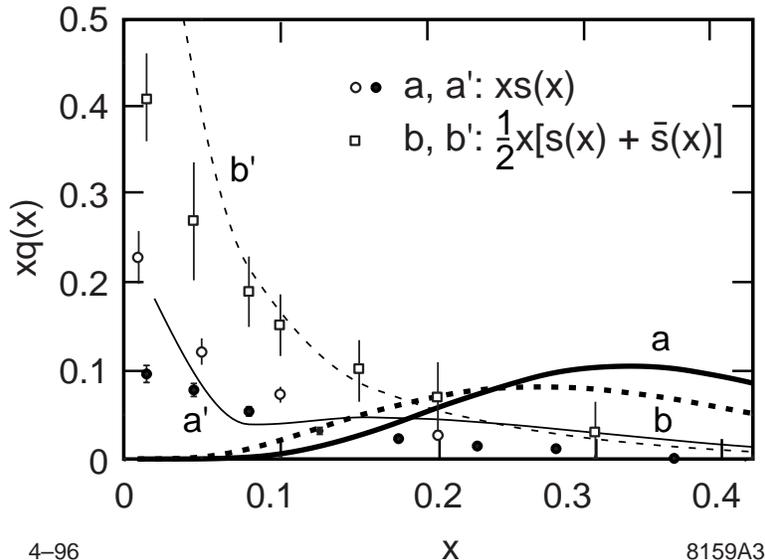


Figure 3: Results for the strange quark distributions $xs(x)$ and $x\bar{s}(x)$ as a function of the Bjorken scaling variable x . The open squares shows the CTEQ determination of $\frac{1}{2}x[s(x) + \bar{s}(x)]$ obtained from $\frac{5}{12}(F_2^{\nu N} + F_2^{\bar{\nu}N})(x)(\text{CCFR}) - 3F_2^{\mu N}(x)(\text{NMC})$. The circles show the CCFR determinations for $xs(x)$ from dimuon events in neutrino scattering using a leading-order QCD analysis at $Q^2 \approx 5(\text{GeV}/c)^2$ (closed circles) and a higher-order QCD analysis at $Q^2 = 20(\text{GeV}/c)^2$ (open circles). 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 the factor $d_v(x)|_{fit}/d_v(x)|_{model}$ assuming a probability of 4% for the $K^+\Lambda$ state.

In principle, the difference between $s(x)$ and $\bar{s}(x)$ can be determined from measurements of deep inelastic scattering by neutrino and antineutrino beams since they probe strange and antistrange quarks in distinct ways. One also requires explicit light-flavor quark distributions $u(x)$, $d(x)$ and $\bar{u}(x)$, $\bar{d}(x)$. The CCFR determinations of the strange quark distributions are obtained from 5044 neutrino and 1062 antineutrino dimuon events by assuming $s(x) = \bar{s}(x)$ [18]. However, we can regard their

results as a rough estimate of $s(x)$ alone since the neutrino events dominate the data set.

In Fig. 3 we plot the calculated $xs(x)$ and $\frac{1}{2}x[s(x) + \bar{s}(x)]$ where the normalization of the $K^+\Lambda$ probability is adjusted to fit the measured strange sea at $x \approx 0.2$. This prediction does not take into account QCD evolution but indicates the inherent quark/antiquark asymmetry predicted by the fluctuation model with the input light-cone wavefunction. In order to reflect the evolution effect we have simply multiplied by a factor $d_v(x)|_{fit}/d_v(x)|_{model}$ in the light-cone quark-spectator model [12] to the calculated $s(x)$ and $\bar{s}(x)$ in our model. Aside from very small x where shadowing may be playing a role, the predictions of the model are in reasonable qualitative agreement with the empirical determinations of $xs(x)$ and $\frac{1}{2}x[s(x) + \bar{s}(x)]$. Thus the quark/antiquark asymmetry of the intrinsic strange quark distributions may help to explain the apparent conflict between the two measures. Of course, the actual wavefunctions underlying the higher Fock states are undoubtedly more complicated than the simple forms used here.

The CCFR collaboration has re-analyzed the strange quark distributions within the context of a higher-order QCD analysis [19]. The discrepancy between the new measured strange quark distributions and those of the CTEQ parametrizations is reduced, but it is still significant. The CTEQ “data” is still larger than the new CCFR data, in agreement with the ratio of $\frac{1}{2}x[s(x) + \bar{s}(x)]$ to $xs(x)$ predicted by the fluctuation model. In Fig. 4 we plot the CTEQ-CCFR “data” for the strange asymmetry $s(x)/\bar{s}(x)$ by combining the CTEQ “data” and the new CCFR data. Allowing for the experimental errors, there is a reasonable agreement between the “data” and the predictions of the LC fluctuation model if we increase the value for the wavefunction momentum scale α . A larger momentum scale α is also required for a good description of structure function within the light-cone quark model [20]. We should be cautious about comparisons in the small x region, since the dominant contribution to strange and antistrange quarks in this region comes from the extrinsic sea quarks as well as the evolution of the intrinsic contributions; in fact, it has been shown that gluon splitting alone is sufficient to describe the data [21].

The CCFR collaboration has made a $s(x) \neq \bar{s}(x)$ fit to their neutrino and antineu-

trino induced dimuon events and did not find clear evidence for a difference between $s(x)$ and $\bar{s}(x)$ [19]. However, within the allowed errors, the CCFR data for $s(x)/\bar{s}(x)$ does not rule out a strange asymmetry of the magnitude suggested by the LC fluctuation model, see Fig. 4. It is also important to note that the CCFR analysis of $s(x)$ and $\bar{s}(x)$ forces the data to fit specific power-law parametrizations which preclude a structured asymmetric intrinsic sea contribution of the type predicted by the LC fluctuation model. Thus the CCFR parametrizations shown in Figs. 3 and 4 may not accurately represent the actual physics and we urge a reanalysis that allows a structured asymmetric intrinsic strange sea. Higher precision data and more studies are clearly needed in order to positively confirm an asymmetry in the momentum distributions of the strange and antistrange quarks.

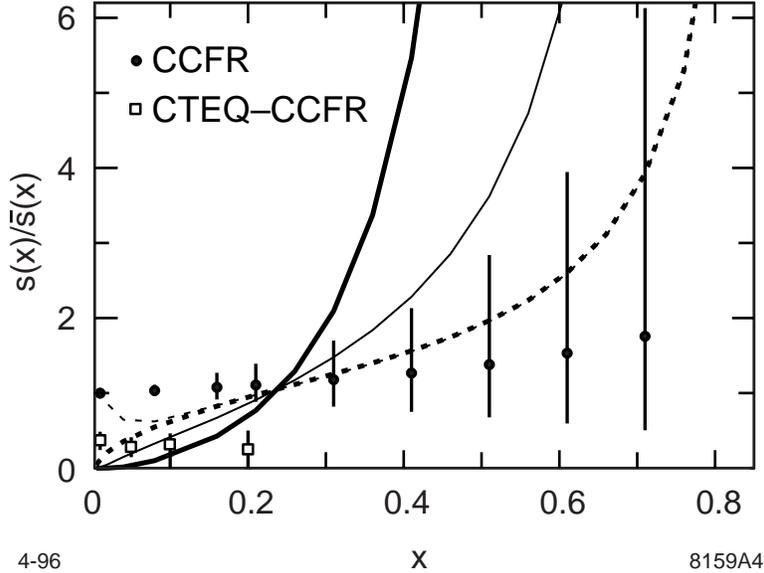


Figure 4: Results for the strange asymmetry $s(x)/\bar{s}(x)$ as a function of the Bjorken scaling variable x . The open squares are the combined CTEQ-CCFR “data” and the closed circles are the CCFR measurement of $s(x)/\bar{s}(x)$. The thick (thin) solid curve is the calculated result of $s(x)/\bar{s}(x)$ in the light-cone meson-baryon fluctuation model for the Gaussian type wavefunction with $\alpha = 330$ (530) MeV. The thick broken curve is the result with a larger $\alpha = 800$ MeV and the thin broken curve is the above result with of about 30% extrinsic strange quarks (*i.e.*, $x s_{extrinsic} = 0.07(1-x)^5$) included for comparison with the CCFR result at small x .

The normalization for intrinsic $s\bar{s}$ fluctuations can be determined by fitting the two “measurements” of the strange quark distributions in the nucleon at $x \approx 0.2$. We find a probability of approximately 10% for intrinsic $s\bar{s}$ pairs. The net spin fraction of the intrinsic strange sea (s_s) quarks is $\Delta S_{s_s} = -\frac{1}{3}$ normalized to the $s\bar{s}$ fluctuation of $K^+\Lambda$. The Wigner rotation factor should be close to 1 due to the larger mass of the strange quarks. Thus the helicity contribution from the intrinsic s_s quarks with Fock state probability 4-15% is $\Delta s_s \approx -0.01$ to 0.05 , which is somewhat smaller than the currently estimated empirical value [22] $\Delta s = -0.10 \pm 0.03$. It is possible that part of this discrepancy is due to the use of exact $SU(3)$ flavor symmetry in the global fit [22], as suggested in Refs. [23].

4 The light-flavor quark content in the nucleon sea

The light-cone 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 quark/antiquark asymmetry in the nucleon sea. The lowest non-neutral $u\bar{u}$ fluctuation in the proton is $p(uud) = \pi^-(d\bar{u})\Delta^{++}(uuu)$, and its probability is small compared to the non-neutral $d\bar{d}$ fluctuation. Therefore the dominant non-neutral light-flavor $q\bar{q}$ fluctuation in the proton sea is $d\bar{d}$ through the meson-baryon configuration $p(uud) = \pi^+(u\bar{d})n(udd)$. 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 [24] for the violation of the Gottfried sum rule [25] and leads to non-trivial distributions of the sea quarks. The NMC measurement $S_G = \frac{1}{3} + \frac{2}{3} \int_0^1 dx [u_s(x) - d_s(x)] = 0.235 \pm 0.026$ [25] implies $\int_0^1 dx [d_s(x) - u_s(x)] = 0.148 \pm 0.039$, which can be considered as the probability of finding non-neutral intrinsic $d\bar{d}$ fluctuations in the proton sea.

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) [26]. 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 explicit x -dependent helicity distributions for valence u and d quarks can be related to the unpolarized valence quark distributions in a light-cone SU(6) quark-spectator model [12] for nucleon structure functions by taking into account the flavor asymmetry due to the difference between scalar and vector spectators and the Wigner rotation effect from the quark transversal motions [6]. Although the SMC data have fairly large errors, the calculated $\Delta u_v(x)$ in the light-cone quark-spectator model are in good agreement with the data. However, the predicted $\Delta d_v(x)$ distributions do not fit the data well and seem to demand an additional negative contribution. 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 $|\Delta u_v| \leq \frac{4}{3}$ and $|\Delta d_v| \leq \frac{1}{3}$. A global fit [22] 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: $\Delta u = 0.83 \pm 0.03$, $\Delta d = -0.43 \pm 0.03$, $\Delta s = -0.10 \pm 0.03$. 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 Δd_s in the nucleon sea.

5 Summary

Intrinsic sea quarks clearly play a key role in determining basic properties of the nucleon, including its static measures such as the strange quark contribution to the nucleon magnetic moments. As we have shown here, the corresponding intrinsic contributions to the sea quark structure functions lead to nontrivial, asymmetric,

and structured momentum and spin distributions. Understanding the role of the intrinsic distributions is essential for setting the boundary conditions for the QCD evolution of the quark sea. Although the sea quarks generated by perturbative leading twist QCD evolution from gluon spitting are necessarily CP and flavor symmetric, this is not true for the momentum and helicity distributions of intrinsic sea quarks controlled by the bound state nature of the hadrons.

In this paper 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 Λ polarization in $\bar{\nu}N$ 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.

We would like to thank X. Ji and M. Burkardt for helpful conversations.

References

- [1] 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.
- [2] M. Burkardt and B. J. Warr, Phys. Rev. **D 45** (1992) 958.
- [3] S. J. Brodsky and D. G. Robertson, SLAC-PUB-95-7056, OSU-NT-95- 06.
- [4] A. I. Signal and A. W. Thomas, Phys. Lett. **B 191** (1987) 205.
- [5] B.-Q. Ma, Phys. Rev. **C 43** (1991) 2821; Int. J. Mod. Phys. **E 1** (1992) 809.
- [6] B.-Q. Ma, J. Phys. **G 17** (1991) L53; B.-Q. Ma and Q.-R. Zhang, Z. Phys. **C 58** (1993) 479; S. J. Brodsky and F. Schlumpf, Phys. Lett. **B 329** (1994) 111.
- [7] A. Manohar and H. Georgi, Nucl. Phys. **B 234** (1984) 189; E. J. Eichten, I. Hinchliffe, and C. Quigg, Phys. Rev. **D 45** (1992) 2269; T. P. Cheng and L. F. Li, Phys. Rev. Lett. **74** (1995) 2872.
- [8] W. Lu and B. -Q. Ma, Phys. Lett. **B 357** (1995) 419.
- [9] J. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. **C 69** (1995) 467.
- [10] WA59 Collab., S. Willocq *et al.*, Z. Phys. **C 53** (1992) 207.
- [11] S. J. Brodsky, M. Burkardt, and I. Schmidt, Nucl. Phys. **B 441** (1995) 197.
- [12] B.-Q. Ma, Preprint BIHEP-TH-95-30, Phys. Lett. **B** (1996) in press.
- [13] 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.
- [14] S. J. Brodsky and I. Schmidt, Phys. Rev. **D 43** (1991) 179.
- [15] CTEQ Collab., J. Botts *et al.*, Phys. Lett. **B 304** (1993) 159; H. L. Lai *et al.*, Phys. Rev. **D 51** (1995) 4763.
- [16] NM Collab., P. Amaudruz *et al.*, Phys. Lett. **B 295** (1992) 159.

- [17] CCFR Collab., Nevis preprints, S. R. Mishra *et al.*, #1459; W. C. Leung *et al.*, #1460; and P. Z. Quintas *et al.*, #1461.
- [18] S. A. Rabinowitz *et al.*, Phys. Rev. Lett. **70** (1993) 134.
- [19] CCFR Collab., A. O. Bazarko *et al.*, Z. Phys. **C 65** (1995) 189.
- [20] T. Huang, B.-Q. Ma, and Q.-X. Shen, Phys. Rev. **D 49** (1994) 1490.
- [21] X. Ji and J. Tang, Phys. Lett. **B 362** (1995) 182.
- [22] J. Ellis and M. Karliner, Phys. Lett. **B 341** (1995) 397.
- [23] B. Ehrnsperger and A. Schäfer, Phys. Lett. **B 348** (1995) 619; J. Lichtenstadt and H. Lipkin, Phys. Lett. **B 353** (1995) 119.
- [24] E. M. Henley and G. A. Miller, Phys. Lett. **B 251** (1990) 453.
- [25] NM Collab., P. Amaudruz *et al.*, Phys. Rev. Lett. **66** (1991) 2712; M. Arneodo *et al.*, Phys. Rev. **D 50** (1994) R1.
- [26] SM Collab., B. Adeva *et al.*, Phys. Lett. **B 369** (1996) 93.