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Asymmetric Quarks in the Proton[1]

W. Melnitchouk

Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide 5005, Australia, and Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606

Abstract. Asymmetries in the quark momentum distributions in the proton reveal fundamental aspects of strong interaction physics. Differences between $\bar{u}$ and $\bar{d}$ quarks in the proton sea provide insight into the dynamics of the pion cloud around the nucleon and the nature of chiral symmetry breaking. Polarized flavor asymmetries allow the effects of pion clouds to be disentangled from those of antisymmetrization. Asymmetries between s and $\bar{s}$ quark distributions in the nucleon are also predicted from the chiral properties of QCD.

INTRODUCTION

Asymmetries in the proton's spin and flavor quark distributions provide direct information about QCD dynamics of bound systems. Differences between quark or antiquark distributions in the proton sea almost universally signal the presence of phenomena which require understanding of strongly coupled QCD. Their existence testifies to the relevance of long-distance dynamics even at large energy and momentum transfers.

Over the past decade a number of high-energy experiments and refined data analyses have forced a re-evaluation of our view of the nucleon in terms of three valence quarks immersed in a sea of perturbatively generated $q\bar{q}$ pairs and gluons [1]. A classic example of this is the asymmetry of the light quark sea of the proton, dramatically confirmed in recent deep-inelastic and Drell-Yan experiments at CERN [2,3] and Fermilab [4]. Less firmly established, but equally intriguing, are asymmetries between quark and antiquark distributions for heavier flavors, such as s and $\bar{s}$, which can be measured in deep-inelastic neutrino scattering experiments [5].

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LIGHT ANTIQUARK ASYMMETRY

Because gluons in QCD are flavor-blind, the sea generated through the perturbative process $g \longrightarrow q\bar{q}$ is symmetric in the quark flavors. Differences can arise due to different quark masses, but because isospin symmetry is such a good symmetry in nature, one expects that the sea of light quarks generated perturbatively would be almost identical, $\bar{u}(x) = \bar{d}(x)$.

It was therefore a surprise to many when measurements by the New Muon Collaboration (NMC) at CERN [2] of the proton and deuteron structure functions suggested a significant excess of $\bar{d}$ over $\bar{u}$ in the proton. Indeed, it heralded a renewed interest in the application of ideas from non-perturbative QCD to deep-inelastic scattering analyses. While the NMC experiment measured the integral of the antiquark difference, more recently the E866 Collaboration at Fermilab has for the first time mapped out the shape of the $\bar{d}/\bar{u}$ ratio over a large range of x, $0.02 < x < 0.345$.

Specifically, the E866/NuSea Collaboration measured $\mu^+\mu^-$ Drell-Yan pairs produced in pp and pd collisions. If x_1 and x_2 are the light-cone momentum fractions carried by partons in the projectile and target, respectively, then in the limit $x_1 \gg x_2$ the ratio of pd and pp cross sections can be written [4]:

$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right) \frac{4 + d(x_1)/u(x_1)}{4 + d(x_1)/u(x_1) \cdot \bar{d}(x_2)/\bar{u}(x_2)} \,, \tag{1}$$

where isospin symmetry has been used to relate quark distributions in the neutron to those in the proton. Corrections for nuclear shadowing in the deuteron [6], which are important at small x, are negligible in the region covered by this experiment.

The relatively large asymmetry found in these experiments, shown in Fig. 1, implies the presence of non-trivial dynamics in the proton sea which does not have a perturbative QCD origin. The simplest and most obvious source of a non-perturbative asymmetry in the light quark sea is the chiral structure of QCD. From numerous studies in low energy physics, including chiral perturbation theory, pions are known to play a crucial role in the structure and dynamics of the nucleon [7].

As pointed out by Thomas [8], if the proton's wave function contains an explicit $\pi^+ n$ Fock state component, a deep-inelastic probe scattering from the virtual π^+, which contains a valence $\bar{d}$ quark, will automatically lead to a $\bar{d}$ excess in the proton. In the impulse approximation, deep-inelastic scattering from the πN component of the proton can then be understood in the infinite momentum frame (IMF) [9] as the probability for a pion to be emitted by the proton, folded with the probability of finding the a parton in the pion. For the antiquark asymmetry, this can be written as [10–14]:

$$\bar{d}(x) - \bar{u}(x) = \frac{2}{3}\int_x^1 \frac{dy}{y} f_{\pi N}(y)\ \bar{d}^{\pi^+}(x/y) \,, \tag{2}$$

where $\bar{d}^{\pi^+}$ is the (valence) $\bar{d}$ quark distribution in the π^+, and the distribution of pions with a recoiling nucleon (the $N \longrightarrow \pi N$ splitting function) is given by [8,10–14]:

$$f_{\pi N}(y) = \frac{3g_{\pi NN}^2}{16\pi^3} \int \frac{d^2\mathbf{k}_T}{(1-y)\,y} \frac{\mathcal{F}_{\pi N}^2(s_{\pi N})}{(M^2 - s_{\pi N})^2} \left(\frac{k_T^2 + y^2 M^2}{1-y} \right) , \tag{3}$$

where $s_{\pi N}$ is the invariant mass squared of the πN system, $s_{\pi N} = (k_T^2 + m_\pi^2)/y + (k_T^2 + M^2)/(1-y)$, and the πNN vertex form factor, $\mathcal{F}_{\pi N}$, plays the role of an ultraviolet cut-off.

Another contribution known to be important for nucleon structure is that from the $\pi\Delta$ component of the nucleon wave function [7]. For a proton initial state, the dominant Goldstone boson fluctuation is $p \to \pi^-\Delta^{++}$, which leads to an excess of $\bar{u}$ over $\bar{d}$. The relative contributions of the πN and $\pi\Delta$ components are determined partly by the πNN and $\pi N\Delta$ vertex form factors. The most direct way to constrain these form factors is through a comparison with the axial form factors for the nucleon and for the N–Δ transition [15]. Within the framework of PCAC the axial form factors are directly related to the corresponding form factors for pion emission or absorption. The data on the axial form factors are best fit, in a dipole parameterization, by a 1.3 (1.02) GeV dipole for the axial N (N–Δ transition) form factor [15], which gives a pion probability in the proton of $\approx$ 13% (10%).

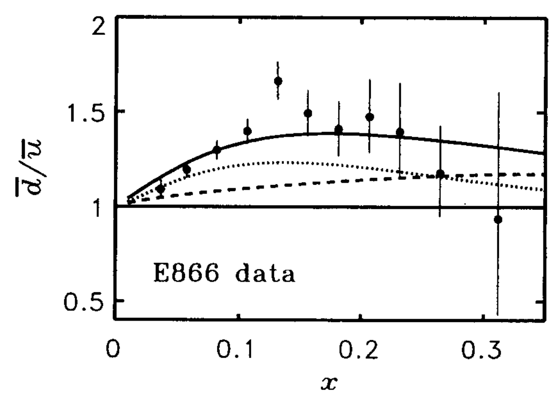

FIGURE 1. Flavor asymmetry of the light antiquark sea, including pion cloud (dashed) and Pauli blocking effects (dotted), and the total (solid) [13].

The resulting $\bar{d}/\bar{u}$ ratio is shown in Fig. 1 (dashed line). Data on the sum of $\bar{u}$ and $\bar{d}$ (which is dominated by perturbative contributions) have been used to convert the calculated $\bar{d} - \bar{u}$ difference to the $\bar{d}/\bar{u}$ ratio. The results suggest that with pions alone one can account for about half of the observed asymmetry, leaving room for possible contributions from other mechanisms. One can fine tune the cut-off parameters, or include other, heavier mesons and baryons in the proton's cloud [14] to obtain a better fit, however, the fact that an asymmetry exists follows directly from the chiral properties of QCD.

In particular, one can derive the non-analytic behavior of flavor asymmetries in the nucleon sea by considering the chiral ($m_\pi \to 0$) limit of Goldstone boson loops. The leading non-analytic (LNA) behavior of the excess number of $\bar{d}$ over $\bar{u}$ quarks in the proton has a chiral behavior typical of loop expansions in chiral effective theories, such as chiral perturbation theory [16]:

$$\int_0^1 dx\, \left(\bar{d}(x) - \bar{u}(x)\right)_{\rm LNA} = \frac{2g_A^2}{(4\pi f_\pi)^2}\, m_\pi^2 \log(m_\pi^2/\mu^2), \tag{4}$$

where μ is an ultraviolet cut-off mass, and the PCAC relation has been used to express the πNN coupling constant in terms of the axial charge, g_A. This result also generalizes to higher moments, each of which has a non-analytic component, so that the $\bar{d} - \bar{u}$ distribution itself, as a function of x, has a model-independent, LNA component. The presence of non-analytic terms indicates that Goldstone bosons play a role which cannot be canceled by any other physical process (except by chance at a particular value of m_π).

Another mechanism which could also contribute to the $\bar{d} - \bar{u}$ asymmetry is associated with the effects of antisymmetrization of $q\bar{q}$ pairs created inside the nucleon [17–19]. As pointed out originally by Field and Feynman [20], because the valence quark flavors are unequally represented in the proton, the Pauli exclusion principle will affect the likelihood with which $q\bar{q}$ pairs can be created in different flavor channels. Since the proton contains two valence u quarks compared with only one valence d quark, $u\bar{u}$ pair creation will be suppressed relative to $d\bar{d}$ creation. In the ground state of the proton the suppression will be in the ratio $\bar{d} : \bar{u} = 5 : 4$ [17].

The shape of the Pauli contribution to the asymmetry is difficult to predict model-independently, but is expected to have an x dependence similar to typical sea quark distributions [17]. Phenomenologically, one finds a good fit for $x < 0.2$ if roughly half of the asymmetry is attributed to antisymmetrization [13,21]. At larger x it is difficult to reproduce the apparent trend in the data towards zero asymmetry, and possibly even an excess of $\bar{u}$ for $x > 0.3$. Unfortunately, the error bars are quite large beyond $x \sim 0.25$, and it is not clear whether new Drell-Yan data will be forthcoming in the near future to clarify this.

A solution may be available, however, through semi-inclusive scattering, in which one tags charged pions produced off protons and neutrons [22]. The HERMES Collaboration has in fact recently measured this ratio [23], although there the rapidly falling cross sections at large x make measurements beyond $x \sim 0.3$ challenging. On the other hand, a high luminosity electron beam such as that available at Jefferson Lab, could allow a precise measurement of the asymmetry beyond $x \sim 0.3$.

The relative roles of pions and Pauli blocking can be further disentangled by measuring the polarized flavor distributions $\Delta\bar{d}$ and $\Delta\bar{u}$ in semi-inclusive scattering [24]. While the antiquark sea due to pions is necessarily unpolarized, the Pauli exclusion principle predicts quite a large asymmetry, $\Delta\bar{u} : \Delta\bar{d} = -4 : 1$ in quark models with SU(6) symmetry [17,18]. By fixing the normalization of the Pauli effect from the polarized asymmetries, one could then determine the size of the pion cloud contribution to $\bar{d} - \bar{u}$.

STRANGENESS IN THE NUCLEON

A complication in studying the light quark sea is the fact that non-perturbative features associated with u and d quarks are intrinsically correlated with the valence core of the proton, so that effects of $q\bar{q}$ pairs can be difficult to distinguish from those of antisymmetrization, or residual interactions of qurks in the core. The strange sector, on the other hand, where antisymmetrization between sea and valence quarks plays no role, is therefore likely to provide even more direct information about the non-perturbative origin of the nucleon sea [25].

Generalizing the formal LNA analysis to the flavor SU(3) sector, one can show that the existence of an asymmetry between s and $\bar{s}$ in the nucleon is predicted on the basis of chiral SU(3) symmetry breaking, which gives rise to a kaon cloud through the fluctuation $N \to KY$, where the hyperon $Y = \Lambda, \Sigma, \cdots$. Since the $\bar{s}$ quark typically comes from the K and the s from the hyperon, the different K and Y masses and momentum distributions naturally lead to differences between s and $\bar{s}$ distributions in the nucleon [26,27]. For the case of the Λ, one has [26,28]:

$$s(x) - \bar{s}(x) = \int_x^1 \frac{dy}{y} \left(f_{YK}(y)\ s^Y(x/y)\ - f_{KY}(y)\ \bar{s}^K(x/y) \right) \ , \qquad (5)$$

where f_{KY} is the analog of the πN splitting function in Eq.(3), and $f_{YK}(y) = f_{KY}(1-y)$. Zero net strangeness in the nucleon implies the vanishing of the lowest moment of $s - \bar{s}$, however, higher moments in general do not vanish. In particular, the LNA behavior of the n-th moment of the $N \to K\Lambda$ splitting function is [16]:

$$\left. f_{K\Lambda}^{(n)} \right|_{\rm LNA} = \frac{27}{25} \frac{M^2 g_A^2}{(4\pi f_\pi)^2} (M_\Lambda - M)^2 (-1)^n \frac{m_K^{2n+2}}{\Delta M^{2n+4}} \log(m_K^2/\mu^2) \ , \qquad (6)$$

where $\Delta M^2 = M_\Lambda^2 - M^2$, and SU(6) symmetry has been used to relate $g_{KN\Lambda}$ to g_A/f_π. Since the LNA terms in the chiral expansion are in general not canceled by other contributions, the process of dynamical symmetry breaking in QCD implies that the s and $\bar{s}$ distributions must have a different dependence on Bjorken x.

The s and $\bar{s}$ distributions can be individually measured in charm production in deep-inelastic ν and $\bar{\nu}$ scattering. Unfortunately, because of relatively large errors the available data from the CCFR collaboration [5], indicated by the shaded region in Fig. 2, are unable to distinguish between zero asymmetry and a small amount of non-perturbative strangeness as would be expected from kaon loops [28] (solid line in Fig. 2). More precise data would be valuable in determining the magnitude, and even the sign, of the asymmetry as a function of x, which depends rather strongly on the dynamics of the KNY interaction [28].

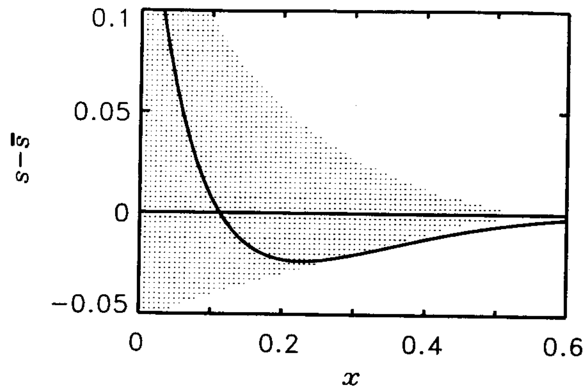

FIGURE 2. Strange quark asymmetry in the proton arising from a kaon cloud of the nucleon [28], with $\approx 3\%$ kaon probability. The shaded region indicates current experimental limits from the CCFR Collaboration [5].

CONCLUSION

We have outlined a number of specific examples where measurement of asymmetries in the sea quark distributions of the nucleon can reveal hitherto hidden details of its non-perturbative structure. Asymmetries are predicted to exist on general grounds from the chiral properties of QCD, by examining the leading non-analytic chiral behavior of quark distributions associated with Goldstone boson loops.

For the $\bar{d}/\bar{u}$ ratio, it is important experimentally to confirm the downward trend of the ratio at large x, which may be feasible through semi-inclusive $\pi^{\pm}$ production. Interestingly, Goldstone boson loops will not give rise to any flavor asymmetries for spin-dependent antiquark distributions, which can only arise from Pauli blocking effects in the proton.

For the strange content of the nucleon, the data from CCFR continue to be reanalyzed in view of possible nuclear shadowing corrections and charm quark effects [29] on s and $\bar{s}$. Together with complementary data on strange form factors currently being gathered in parity-violating elastic electron scattering experiments [30], this will provide valuable information about the role of non-perturbative strangeness in the nucleon.

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