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#### FLAVOR DECOMPOSITION OF THE NUCLEON <sup>a</sup>

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I review some recent developments in the study of quark flavor distributions in the nucleon, including (i) valence quark distributions and the quark-hadron duality prediction for the  $x \rightarrow 1$   $F_2^p/F_2^n$  ratio (ii) sea quark asymmetries and electromagnetic form factors (iii) strange quarks in the nucleon.

#### 1 Introduction

While the problem of how the proton's *spin* is distributed among its constituents continues to captivate the attention of a large segment of the hadron physics community<sup>1</sup> and stimulate development of new approaches to the problem<sup>2</sup>, the question of how the proton's momentum is distributed among its various *flavors* is far from being satisfactorily answered. Recent experiments and refined data analyses have indeed forced us to go far beyond the naive view of a nucleon as three non-relativistic valence quarks in a sea of perturbatively generated  $q\bar{q}$  pairs and gluons<sup>3</sup>.

A classic example of this is the asymmetry of the light quark sea, dramatically confirmed in the recent Drell-Yan experiment at Fermilab<sup>4</sup>, whose interpretation defies any perturbative understanding<sup>5</sup>. In a self-consistent representation of the nucleon, the dynamics responsible for any non-perturbative effects visible in quark distributions should also leave traces in other flavor-sensitive observables such as electromagnetic form factors. One can quantitatively study the connection between the quark distributions and form factors in the context of non-forward parton distributions, which is one of the offshoots of the recent proton spin decomposition studies<sup>2</sup>. As discussed in Section 3, an important test of any realistic model of nucleon structure is that it be able to account not only for the asymmetries in sea quark distributions such as

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the  $\bar{d}/\bar{u}$  ratio, but also observables such as the electric form factor of neutron, which is particularly sensitive to the spin-flavor dynamics of quarks.

Less firmly established, but quite likely to exist nonetheless, are asymmetries between quark and antiquark distributions for heavier flavors, such as  $s$  and  $\bar{s}$ , and even  $c$  and  $\bar{c}$ , which are discussed in Section 4. These are closely connected with the strangeness form factors of the nucleon which are currently receiving much attention from theory and experiment alike.

At the same time as the proton continues to reveal a rich substructure of its sea, some important details of quark distributions in the valence region still remain elusive. Most conspicuous of these is the valence  $d$  quark distribution, or the  $d/u$  ratio, whose  $x \rightarrow 1$  limit remains controversial<sup>6,7</sup>. A number of proposals<sup>8</sup> have been made recently for determining the large- $x$  behavior of  $d/u$  in semi-inclusive deep-inelastic scattering and other high-energy processes. In Section 2 I recall an old prediction for the  $d/u$  ratio at large  $x$  based on empirical observations of quark-hadron duality first made nearly 3 decades ago.

## 2 Valence Quarks and Quark-Hadron Duality

The valence  $d/u$  ratio contains important information about the spin-flavor structure of the proton<sup>9</sup>, and its asymptotic  $x \rightarrow 1$  behavior reflects the mechanism(s) responsible for the breaking of  $SU(2)_{\text{spin}} \times SU(2)_{\text{flavor}}$  symmetry. There are a number of predictions for this ratio, ranging from 1/2 in the non-relativistic  $SU(6)$  quark model, to 0 in broken  $SU(6)$  with scalar-isoscalar spectator quark dominance<sup>10</sup>, to 1/5 in perturbative QCD<sup>11</sup>. Indeed, this is one of the very few predictions for the  $x$ -dependence of parton distributions which can be drawn from perturbative QCD, and its verification or failure would be an important indicator of the appropriate kinematics at which QCD can be treated perturbatively.

The biggest obstacle to an unambiguous determination of  $d/u$  at large  $x$  is the fact that this ratio is extracted from the ratio of inclusive neutron and proton structure functions, with the former never measured directly but rather inferred from proton and deuteron cross sections. The deuteron cross sections, however, must be corrected for nuclear effects in the structure function, which can become quite significant<sup>12,13</sup> at large  $x$ . In particular, whether one corrects for Fermi motion only, or in addition for binding and nucleon off-shell effects, the extracted neutron structure function for  $x > 0.7$  can differ dramatically<sup>6</sup>. The original observation<sup>6</sup> that the  $d/u$  ratio, when corrected for nuclear effects in deuterium, is larger than the value assumed in global data parameterizations was confirmed recently in a subsequent reanalysis<sup>14</sup> based on the assumption

that the nuclear corrections scale with nuclear density<sup>12</sup>. While this may be a reasonable assumption for heavy nuclei such as <sup>56</sup>Fe or <sup>40</sup>Ca, it is rather speculative when applied to light nuclei such as the deuteron. Nevertheless, the conclusions of both analyses do suggest that the neutron structure function may be significantly underestimated through the neglect of nuclear effects.

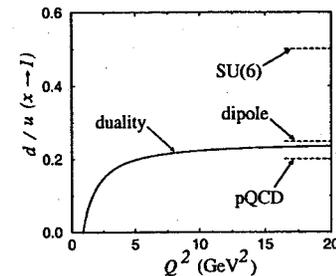


Figure 1: Quark-hadron duality prediction for the  $x \rightarrow 1$  behavior of the  $d/u$  ratio.

While a number of suggestions have been made how to avoid the nuclear contamination problem<sup>8</sup>, one of the more direct ways is to measure relative yields of  $\pi^+$  and  $\pi^-$  mesons in semi-inclusive deep-inelastic scattering from protons<sup>15</sup>. At large  $z$  ( $z$  being the energy of the pion relative to the photon) the  $u$  quark fragments primarily into a  $\pi^+$ , while a  $d$  fragments into a  $\pi^-$ , so that at large  $x$  the ratio  $R^\pi = \sigma(\pi^-)/\sigma(\pi^+)$  is given by the ratio  $d/u$  weighted by  $q \rightarrow \pi$  fragmentation functions. Indeed, in the limit  $z \rightarrow 1$ , where the  $u \rightarrow \pi^+$  fragmentation function dominates<sup>15</sup>, the ratio  $R^\pi \rightarrow d/4u$ .

A direct semi-inclusive measurement of fast pion production will require relatively large  $Q^2$  and  $W^2$ , which may not be feasible until a facility such as an upgraded 12 GeV electron beam at Jefferson Lab becomes available. In the meantime, one must look for clues from other sources for information about  $d/u$  at large  $x$ , and one of the more obscure ones is the phenomenon of quark-hadron duality in inelastic structure functions.

As observed originally by Bloom and Gilman<sup>16</sup>, when averaged over some interval of  $\omega' = (2M\nu + M^2)/Q^2$ , or more precisely<sup>17</sup> the Nachtmann scaling variable  $\xi = 2x/(1 + \sqrt{1 + 4M^2x^2/Q^2})$ , the inclusive structure function in the resonance region at low  $W$  is approximately equal to the scaling structure func-

tion at much larger  $Q^2$ . This was later reinterpreted by de Rújula, Georgi and Politzer<sup>17</sup> in terms of an operator product expansion of the Nachtmann moments of  $F_2$ , in which the equality of the low moments was understood to arise from the relatively small size of higher twist ( $1/Q^2$  suppressed) contributions compared with the leading twist.

Recent experiments at Jefferson Lab<sup>18</sup> confirm that this observation is reasonably accurate for each of the low-lying resonances, including the extreme case of elastic scattering. If one takes the latter seriously, then the first moment of the elastic structure function of the proton is given by the electromagnetic form factors<sup>17,19</sup>:

$$\int_{\xi_{th}}^1 d\xi F_2^{e1}(\xi, Q^2) = \frac{\xi_0^2}{2 - \xi_0} G(Q^2), \quad (1)$$

where  $\xi_{th}$  is the value of  $\xi$  at the pion threshold, and

$$G(Q^2) = \frac{1}{1 + \tau} (G_E^2(Q^2) + \tau G_M^2(Q^2)), \quad (2)$$

with  $\tau = Q^2/4M^2$  and  $\xi_0 = 2/(1 + \sqrt{1 + 1/\tau})$  is the value of  $\xi$  at  $x = 1$ . Differentiating both sides of Eq.(1) with respect to  $Q^2$  gives<sup>16</sup>:

$$\left. \frac{F_2^n(x, Q^2)}{F_2^p(x, Q^2)} \right|_{x \rightarrow 1} = \frac{dG^n(Q^2)/dQ^2}{dG^p(Q^2)/dQ^2}, \quad (3)$$

where

$$\frac{dG}{dQ^2} = \frac{G_M^2 - G_E^2}{4M^2(1 + \tau)^2} + \frac{1}{(1 + \tau)} \left( \frac{dG_E^2}{dQ^2} + \tau \frac{dG_M^2}{dQ^2} \right). \quad (4)$$

Using empirical values for the form factors and inverting  $F_2^n/F_2^p$  gives the local duality prediction for the  $d/u$  ratio in the  $x \rightarrow 1$  limit in Fig.1. If one further assumes that both the proton and neutron magnetic form factors have the same dipole form at large  $Q^2$ , then  $d/u \rightarrow (\mu_n^2 - 4\mu_n^2)/(\mu_n^2 - 4\mu_p^2) \approx 0.25$  in the limit  $Q^2 \rightarrow \infty$ .

It's interesting to observe that above  $Q^2 \approx 5 \text{ GeV}^2$  the duality prediction is similar numerically to the expectation from perturbative QCD. This is consistent with the operator product expansion interpretation of de Rújula et al.<sup>17</sup> in which duality should be a better approximation with increasing  $Q^2$ . Whether this is a coincidence or an indicator of common underlying physics remains to be settled by future experiments.

### 3 Role of the Light Quark Sea

The  $\bar{d}/\bar{u}$  ratio is an important testing ground for our ideas about the long-range structure of the nucleon, and the origin of the non-perturbative spin-flavor interaction. The latest round of discussion about the proton's  $\bar{d}$  and  $\bar{u}$  distributions has been spurred on by the recent measurement by the E866 Collaboration<sup>4</sup> at Fermilab of the  $x$ -dependence of the  $pd$  to  $pp$  cross section ratio for Drell-Yan production, which is sensitive to the  $\bar{d}/\bar{u}$  ratio at small  $x$ .

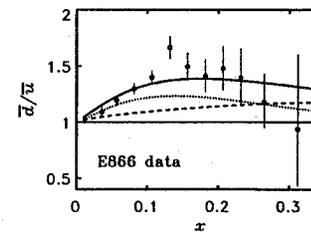


Figure 2: Flavor asymmetry of the light antiquark sea, including pion cloud (dashed) and Pauli blocking effects (dotted), and the total (solid)<sup>5</sup>.

As pointed out originally by Field and Feynman<sup>20</sup>, because the valence quark flavors are unequally represented in the proton, the Pauli exclusion principle implies that  $\bar{u}\bar{u}$  pair creation is suppressed in the proton relative to  $\bar{d}\bar{d}$ . Later, Thomas<sup>21</sup> observed that an excess of  $\bar{d}$  quarks in the proton also arises naturally from the chiral structure of QCD, in the form of a pion cloud. In simple terms, if part of the proton's wave function has overlap with a virtual  $\pi^+n$  state, a deep-inelastic probe scattering from the virtual  $\pi^+$ , which contains a valence  $\bar{d}$  quark, will automatically lead to  $\bar{d} > \bar{u}$  in the proton.

Whatever the ultimate origin of the asymmetry, it is likely to involve some non-perturbative spin-flavors interaction between quarks. In order to identify the different possible origins of the asymmetry, consider a model of the nucleon in which the nucleon core consists of valence quarks, possibly interacting via exchange of gluons, with sea quark effects introduced through the coupling of the core to  $q\bar{q}$  states with light meson quantum numbers (many variants of such a model exist — see for example Refs.<sup>22,23</sup>). In practice, because of

their pseudo-Goldstone nature and their anomalously light mass, the pseudoscalar pions (and for strange observables, kaons) are the most important  $q\bar{q}$  states. The effects of the Pauli exclusion principle on the  $\bar{d}/\bar{u}$  ratio can then be associated with antisymmetrization of  $q\bar{q}$  pairs created inside the core<sup>24</sup>.

Figure 2 shows the  $\bar{d}/\bar{u}$  ratio in the proton including flavor symmetry breaking effects generated by a pion cloud, with both  $N$  and  $\Delta$  recoil states (for soft hadronic form factors the contributions from heavier mesons and baryons are small<sup>25,26</sup>), and a contribution due to the Pauli blocking effect<sup>5</sup>. The pion cloud parameters, namely the hadronic  $\pi NN$  and  $\pi N\Delta$  vertex form factors, are taken from the measured values of the axial elastic  $N$  and  $N\Delta$  transition form factors<sup>27</sup>, and give an overall pion probability in the proton of  $\approx 10-15\%$ .

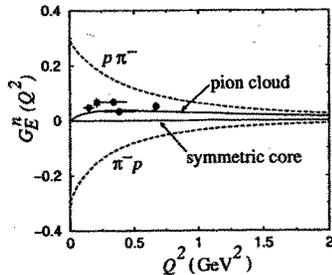


Figure 3: Neutron electric form factor in the pion cloud model.

If a pseudoscalar cloud of  $q\bar{q}$  states plays an important role in the  $\bar{d}/\bar{u}$  asymmetry, its effects should also be visible in other flavor-sensitive observables, such as electromagnetic form factors. An excellent example is the electric form factor of the neutron, a non-zero value for which can arise from a pion cloud,  $n \rightarrow p\pi^-$ . Although in practice other effects<sup>28,29</sup> such as spin-dependent interactions due to one gluon exchange between core quarks may also contribute to  $G_E^n$ , it is nevertheless important to test the consistency of the above model by evaluating its consequences for all observables that may carry its signature.

To illustrate the sole effect of the pion cloud, all residual interactions between quarks in the core are switched off, so that  $G_E^n$  has only two contributions: one in which the photon couples to the virtual  $\pi^-$  (labeled " $\pi^- p$ " in

Fig.3) and one where the photon couples to the recoil proton (" $p\pi^-$ " in Fig.3). Both contributions are large in magnitude but opposite in sign, so that the combined effects cancel to give a small positive  $G_E^n$ , consistent with the data.

One should stress that *the same* pion cloud parameters are used in the calculation of  $G_E^n$  as for the  $\bar{d}/\bar{u}$  asymmetry in Fig.4. Note, however, that the Pauli blocking effect plays no role in form factors, since any suppression of  $\bar{u}$  relative to  $\bar{d}$  here would be accompanied by an equal and opposite suppression of  $u_{\text{sea}}$  relative to  $d_{\text{sea}}$ , and form factors measure charge conjugation odd (i.e. valence) combinations of flavors. The fact that the model prediction slightly underestimates the strength of the observed  $G_E^n$  suggests that other mechanisms, such as one gluon exchange between quarks in the core<sup>28</sup>, could be responsible for some of the difference.

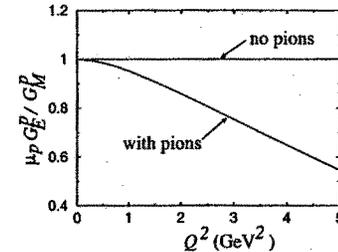


Figure 4: Electric to magnetic proton form factor ratio, with and without a pion cloud.

Another quantity sensitive to details of the flavor distributions in the proton is the electric to magnetic form factor ratio, which was recently measured at Jefferson Lab<sup>30</sup>. Perturbative QCD predicts that asymptotically this ratio should be  $Q^2$ -independent<sup>31</sup>, so that any deviation from a constant ratio would be due to the influence of non-perturbative dynamics. Again assuming a symmetric core which leaves  $\mu_p G_E^p = G_M^p$  for all  $Q^2$ , the pion cloud contribution to the Pauli form factor is suppressed in  $G_E^p$  relative to that in  $G_M^p$ , resulting in the softening of the  $G_E^p/G_M^p$  ratio. Compared with a dipole parameterization, the pion corrections leave  $G_M^p$  relatively unaffected, but make  $G_E^p$  softer, leading to the ratio in Fig.4.

More quantitative comparisons with data would require one to consider more sophisticated models of the nucleon, incorporating explicitly the dynamics of core quarks as well as  $q\bar{q}$  pairs. These simple examples, however, serve

to illustrate the point that the structure and interactions of light quarks and antiquarks in both electromagnetic form factors and high-energy scattering are far richer than could ever be inferred from perturbative QCD.

#### 4 Strange Quarks 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. The strange sector, on the other hand, where antisymmetrization between sea and valence quarks plays no role, is therefore more likely to provide direct information about the non-perturbative origin of the nucleon sea<sup>32</sup>.

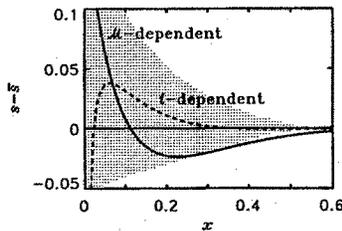


Figure 5: Strange quark asymmetry in the proton arising from meson clouds for two different  $KNY$  form factors. The shaded region indicates current experimental limits from the CCFR Collaboration<sup>33</sup>.

Two related observables which would indicate the presence of non-perturbative strange quarks are the  $s - \bar{s}$  quark distribution asymmetry, and strange electromagnetic form factors. Limits on the former have been obtained from charm production cross sections in  $\nu$  and  $\bar{\nu}$  deep-inelastic scattering, which probes the  $s$  and  $\bar{s}$  distributions in the nucleon, respectively<sup>33</sup>. The resulting difference  $s - \bar{s}$ , indicated in Fig.5 by the shaded area, is consistent with zero, but also consistent with a small amount of non-perturbative strangeness, which would be generated from a kaon cloud around the nucleon<sup>34</sup>, as in chiral quark models or  $SU(3)$  chiral perturbation theory. Indeed, the simplest models of intrinsic

strangeness in the nucleon assume that the strangeness is carried by its  $KY$  ( $Y = \Lambda, \Sigma, \dots$ ) components, so that the  $s$  and  $\bar{s}$  quarks have quite different origins<sup>23,35</sup>.

The kaon cloud contribution to the asymmetry is shown by the solid curve in Fig.5, for a kaon probability of  $\approx 3\%$ . Because the  $\bar{s}$  distribution in a kaon is much harder than the  $s$  distribution in a hyperon, the resulting  $s - \bar{s}$  difference will be negative at large  $x$ , despite the kaon distribution in the nucleon being slightly softer than the hyperon distribution (on the light cone). However, contrary to recent claims in the literature, a kaon cloud does not unambiguously predict the sign of the  $s - \bar{s}$  difference as a function of  $x$ , which turns out to be very sensitive to the dynamics of the  $KNY$  vertex<sup>34</sup>. To demonstrate this the asymmetry is calculated for two different  $KNY$  form factors, one which depends on the invariant-mass  $M$  of the  $KY$  state<sup>26,34</sup> (solid), and one which depends on the exchanged four-momentum  $t$  (dashed). For the latter, the  $K$  distribution in the nucleon is somewhat softer than the  $\Lambda$ , which in this case does overcompensate for the harder  $\bar{s}$  distribution in  $K$ <sup>34</sup>. Better precision neutrino data would therefore be extremely helpful in determining just how asymmetric strangeness in the nucleon is.

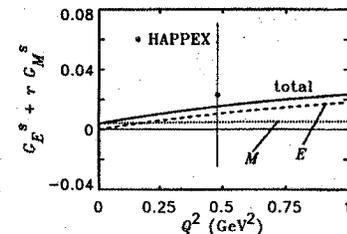


Figure 6: Strange electromagnetic form factors of the proton compared with a kaon cloud prediction. For the HAPPEX data<sup>37</sup>,  $\tau \approx 0.4$ .

The other way to determine the size of the non-perturbative strange asymmetry in the nucleon is to measure the strange contributions to the elastic electromagnetic form factors, as has recently been done at MIT-Bates<sup>36</sup> and Jefferson Lab<sup>37</sup>. The latest experimental information on the strange electric and magnetic form factors is shown in Fig.6, together with the kaon cloud

prediction using the same parameters for the  $KVY$  vertex as in the  $s - \bar{s}$  asymmetry in Fig.5. The result is a small and slightly positive<sup>34</sup> value for the  $G_E^s$  and  $G_M^s$  combination measured in the HAPPEX experiment<sup>5</sup>. Although in good agreement with the available data, clearly better limits on  $G_{E/M}^s$  will be needed in order to provide conclusive evidence for or against the presence of a tangible non-perturbative strange component in the nucleon.

## 5 Future

One can anticipate progress to be made on each of the issues addressed here in the near future, as better quality data from high energy, high luminosity facilities, capable of accessing extreme kinematic regions, become available. The semi-inclusive production of  $\pi^\pm$  is an example of a straightforward way to cleanly extract the  $d/u$  ratio at large  $x$ , free of the nuclear contamination inherent in earlier analyses. Once this is achieved, the origin of the SU(6) symmetry breaking responsible for the softening of the  $d$  quark distribution may be within reach.

For the  $\bar{d}/\bar{u}$  ratio, it is important experimentally to confirm the downward trend of the ratio at large  $x$ , where pion cloud models generally predict a flattening out rather than any dramatic decrease in  $\bar{d}/\bar{u}$ . Issues concerning the size of the gluon contribution at large  $x$  may need to be resolved, however, before definitive conclusions from the present data can be reached. Future measurements of the neutron's electric form factor at Jefferson Lab and elsewhere, as well as the  $Q^2$ -dependence of the proton's form factors at large  $Q^2$ , should provide critical tests of our understanding of the dynamics of light quarks in the nucleon and the origin of the non-perturbative spin-flavor interaction.

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<sup>39</sup>. The strange form factors will also be measured to better precision in the upcoming HAPPEX II experiment and subsequent experiments at Jefferson Lab.

## Acknowledgments

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<sup>34</sup>The result of a new measurement of the  $G_M^s$  form factor just announced by the SAMPLE Collaboration<sup>38</sup> gives a value  $+0.61 \pm 0.17 \pm 0.21$  at  $Q^2 = 0.1$  GeV<sup>2</sup>, providing the strongest evidence yet for a non-zero strange asymmetry in the proton.

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