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On the momentum dependence of the flavor structure of the nucleon sea

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ABSTRACT

Difference between the $\bar{u}$ and $\bar{d}$ sea quark distributions in the proton was first observed in the violation of the Gottfried sum rule in deep-inelastic scattering (DIS) experiments. The parton momentum fraction x dependence of this difference has been measured over the region $0.02 < x < 0.35$ from Drell–Yan and semi-inclusive DIS experiments. The Drell–Yan data suggested a possible sign-change for $\bar{d}(x) - \bar{u}(x)$ near $x \sim 0.3$, which has not yet been explained by existing theoretical models. We present an independent evidence for the $\bar{d}(x) - \bar{u}(x)$ sign-change at $x \sim 0.3$ from an analysis of the DIS data. We further discuss the x-dependence of $\bar{d} - \bar{u}$ in the context of meson cloud model and the lattice QCD formulation.

It is now a well established fact that the $\bar{u}$ and $\bar{d}$ distributions in the proton are strikingly different. The first evidence for this difference came from the observation of the violation of the Gottfried sum rule [1] in a deep-inelastic scattering (DIS) experiment by the NMC Collaboration [2]. The Gottfried sum rule, $I_G \equiv \int_0^1 [F_2^p(x_B) - F_2^n(x_B)]/x_B \, dx_B = 1/3$, is obtained under the assumption of a symmetric $\bar{u}$ and $\bar{d}$ sea [1], where x_B is the Bjorken variable and is effectively equal to parton momentum fraction x probed in DIS using the leading order QCD factorization formalism of the structure function $F_2(x_B)$. The NMC measurement of $I_G = 0.235 \pm 0.026$ implies that this assumption is invalid with an x-integrated difference of $\int_0^1 [\bar{d}(x) - \bar{u}(x)] dx = 0.148 \pm 0.039$.

The NMC result was subsequently checked using two independent experimental techniques. From measurements of the Drell–Yan cross section ratios of $[\sigma(p+d)]/[\sigma(p+p)]$, the NA51 [3] and the Fermilab E866 [4] experiments measured $\bar{d}/\bar{u}$ as a function of x over the kinematic range of $0.015 < x < 0.35$. As shown in Fig. 1, the $\bar{d}/\bar{u}$ ratios clearly differ from unity. From a semi-inclusive DIS measurement, the HERMES Collaboration also reported the observation [5] of $\bar{d}(x) - \bar{u}(x) \neq 0$, consistent with the Drell–Yan results.

The $\bar{d}(x)/\bar{u}(x)$ data obtained from the Drell–Yan experiments have provided stringent constraints for parameterizing the parton distribution functions (PDFs). Fig. 1 compares the data measured at $Q^2 = 54$ GeV^2 from Fermilab E866 with parameterizations of several PDFs. The E866 data show the salient feature that $\bar{d}/\bar{u}$ rises linearly with x for $x < 0.15$ and then drops as x further increases. At the largest value of x ($x = 0.315$), the $\bar{d}/\bar{u}$ ratio falls below unity, albeit with large experimental uncertainty. This intriguing x-dependence of $\bar{d}/\bar{u}$ is reflected in recent PDFs including CTEQ6 [6], CT10 [7], MSTW08 [8], and JR14 [9]. However, for the CTEQ4M [10] PDF, which predated the E866 data, the $\bar{d}/\bar{u}$ ratios at large x are not well described by the parameterizations. In particular, $\bar{d}(x)/\bar{u}(x)$ remains greater than unity, or equivalently, $\bar{d}(x) - \bar{u}(x) > 0$, at all x. The parameterizations of the more recent PDFs are sufficiently flexible to accommodate a sign-change for $\bar{d}(x) - \bar{u}(x)$ at $x \sim 0.3$, as suggested by the E866 data.

Many theoretical models have been put forward to explain the surprisingly large difference between $\bar{d}(x)$ and $\bar{u}(x)$. For reviews on various theoretical models, see Refs. [11–15]. While these models can explain the enhancement of $\bar{d}$ over $\bar{u}$ involving various mechanisms such as meson cloud, chiral-quark, intrinsic sea, soliton, and Pauli-blocking, none of them predicts that the $\bar{d}/\bar{u}$ ratio falls below unity at any value of x [14]. In order to understand the origin of the sea-quark flavor structure, it is important to improve the

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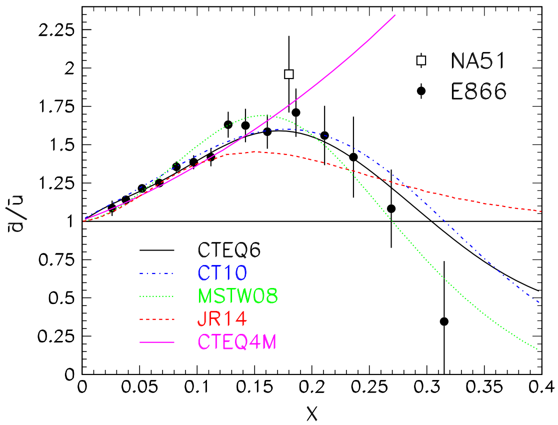

Fig. 1. Ratio of $\bar{d}(x)$ over $\bar{u}(x)$ versus Bjorken-x from experiments NA51 [3] and E866 [4]. Parameterizations from several parton distribution functions are also shown.

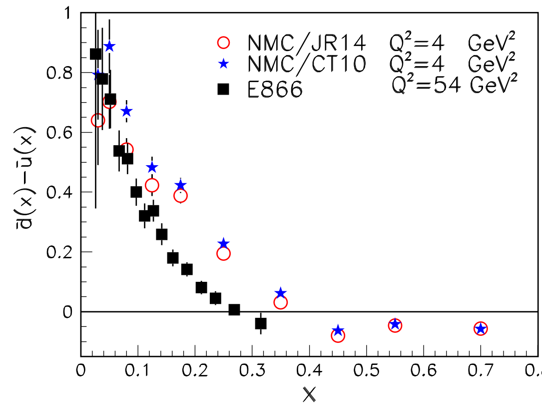

Fig. 2. Values of $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 4$ GeV^2 evaluated using Eq. (2), as discussed in the text. The open circles and filled stars correspond to results obtained with the JR14 and CT10 PDFs, respectively. Also shown are the values of $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 54$ GeV^2 from the Fermilab E866 experiment.

accuracy and to extend the kinematic coverage of the $\bar{d}/\bar{u}$ measurement to the $x > 0.3$ region. This is the goal of an ongoing Fermilab Drell–Yan experiment, E906 [16], and a proposed experiment [17] at the J-PARC facility. The x-dependence of $\bar{d}/\bar{u}$ (or the related quantity $\bar{d} - \bar{u}$) at large x remains a topics of much interest both theoretically and experimentally.

In this paper we address the intriguing possibility that $\bar{d} - \bar{u}$ changes sign at the $x \sim 0.3$ region. We first show that an independent experimental evidence for this sign-change, other than the one shown in Fig. 1 from the Drell–Yan data, comes from an analysis of the NMC DIS data. We then discuss the significance of this sign-change and the stringent constraint it imposes on theoretical models. We also discuss the implications on the x-dependence of $\bar{d} - \bar{u}$ using the lattice QCD formulation for the sea-quark parton distributions. Future measurements of $\bar{d}(x)/\bar{u}(x)$ at $x > 0.25$ in Drell–Yan experiments could provide strong constraints and new insights on the origins of the flavor structure of the proton's sea.

The NMC measurement of the Gottfried sum involves the F_2 structure functions on proton and neutron. In terms of QCD factorization, we have at the leading order in α_s,

$$F_2^p(x) - F_2^n(x) = \frac{1}{3}x\big[u(x) + \bar{u}(x) - d(x) - \bar{d}(x)\big], \tag{1}$$

where $x = x_B$ was used at this order. Eq. (1) is obtained under the usual assumption of charge symmetry of parton distributions and the equality of heavy-quark (s, c, b) distributions in proton and neutron. Note that the Q^2 dependence in $F_2^{p,n}(x, Q^2)$ and parton distributions $q(x, Q^2)$ is implicit. The magnitude of order α_s^1 and α_s^2 perturbative QCD effect is estimated to be small, on the order of 0.2% at $Q = 10$ GeV [18]. From Eq. (1) and the definition of valence quarks, $u_v(x) = u(x) - \bar{u}(x)$ and $d_v(x) = d(x) - \bar{d}(x)$, one readily obtains the following expression:

$$\bar{d}(x) - \bar{u}(x) = \frac{1}{2}\big[u_v(x) - d_v(x)\big] - \frac{3}{2x}\big[F_2^p(x) - F_2^n(x)\big]. \tag{2}$$

Eq. (2) shows that the x dependence of $\bar{d} - \bar{u}$ can be extracted from the NMC measurement of $F_2^p(x) - F_2^n(x)$ and the parametrization of $u_v(x) - d_v(x)$ from various PDFs. To illustrate this, we show in Fig. 2 the values of $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 4$ GeV^2 using Eq. (2), where the first term of the right-hand side, $u_v(x) - d_v(x)$, is taken from the NNLO JR14 parametrization [9] and the second term, $F_2^p(x) - F_2^n(x)$, is taken from the NMC data [2] at $Q^2 = 4$ GeV^2. The JR14 is a recent PDF where the nuclear corrections from the CJ group [19] is implemented and $\bar{d}(x) - \bar{u}(x) > 0$ is assumed at all x in the global analysis. We also show in Fig. 2 the values of $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 54$ GeV^2 (filled squares) derived by the E866 Collaboration [4]. The sign-change of $\bar{d} - \bar{u}$ at $x \sim 0.3$ as indicated by the E866 data is clearly consistent with the behavior of open circles obtained by using Eq. (2) based on the NMC data and the JR14 PDFs. Although the JR14 uses a parametrization of $\bar{d} - \bar{u}$ that is positive at all x, as shown in Fig. 1, we demonstrated in Fig. 2 that NMC data together with the valence quark distributions of JR14 could lead to a sign-change of $\bar{d}(x) - \bar{u}(x)$ distribution at $x \sim 0.3$. We have also performed calculations with other sets of recent PDFs, obtained very similar results and reached the same conclusion. In Fig. 2, we show, for example, the values of $\bar{d}(x) - \bar{u}(x)$ (filled stars) obtained by using $u_v(x) - d_v(x)$ of the CT10 PDF parametrization [7] along with the same NMC data. The values of $\bar{d}(x) - \bar{u}(x)$ obtained by using CT10 and JR14 are practically identical for $x > 0.2$. This finding is effectively a consequence of the fact that the $u_v(x) - d_v(x)$ distribution in Eq. (2) is well constrained by QCD global fit of the extensive DIS and hadronic scattering data.

Although Fig. 2 shows similar trends for the x-dependence of $\bar{d} - \bar{u}$ extracted from the E866 Drell–Yan and the NMC DIS data, these two data sets correspond to two different Q^2 scales. A more direct comparison can be obtained by analyzing the final results published by the NMC Collaboration on the ratio $R(x) = F_2^d(x)/F_2^p(x)$ [20]. The values of $F_2^p(x) - F_2^n(x)$ could be calculated from $2F_2^d(x) * (1/R(x) - 1/r_N^d(x))$, by using the parametrization of $F_2^d(x)$ of Ref. [21]. The $r_N^d(x)$ is the ratio of deuteron to isoscalar nucleon structure functions $F_2^d(x) = r_N^d(x) * (F_2^p(x) + F_2^n(x))/2$ and we use $r_N^d(x)$ of the CJ12mid set at $Q^2 = 100$ GeV^2 [22] for the evaluation. Refs. [20] and [21] included not only additional data that were not available for NMC's earlier evaluation of the Gottfried sum [2], but also the values of $R(x)$ at different bins of Q^2 ranging from 0.16 to 99.03 GeV^2. The high Q^2 data makes it possible to compare the E866 Drell–Yan data on $\bar{d}(x) - \bar{u}(x)$ at $Q^2 = 54$ GeV^2 with that evaluated using Eq. (2) and NMC data at a similar Q^2. As the E866 Drell–Yan data on $\bar{d}(x) - \bar{u}(x)$ correspond to $Q^2 = 54$ GeV^2, a comparison could be made by using the NMC data at similar Q^2. The mean values of Q^2 for the four highest Q^2 bins of NMC data are around 34, 45, 63, and 95 GeV^2. Fig. 3 shows $\bar{d}(x) - \bar{u}(x)$ for these four values of Q^2 using Eq. 2 with the JR14 parametrization of the valence quark distributions and the NMC data [20] for $F_2^p(x) - F_2^n(x)$. The uncertainties of both $R(x)$ and the parametrization of F_2^d have been included in the evaluation of $F_2^p(x) - F_2^n(x)$. Fig. 3 shows that the values of $\bar{d}(x) - \bar{u}(x)$ at $x > 0.3$ are mostly negative with the mean values of -0.009 ± 0.006, -0.012 ± 0.006, -0.016 ± 0.008, and -0.001 ± 0.008, respectively,