$\bar{d}/\bar{u}$ Asymmetry and the Origin of the Nucleon Sea

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The Drell-Yan cross section ratios, $\sigma(p+d)/\sigma(p+p)$, measured in Fermilab E866, have led to the first determination of $\bar{d}(x)/\bar{u}(x)$, $\bar{d}(x)-\bar{u}(x)$, and the integral of $\bar{d}(x)-\bar{u}(x)$ for the proton over the range $0.02 \leq x \leq 0.345$. The E866 results are compared with predictions based on parton distribution functions and various theoretical models. The relationship between the E866 results and the NMC measurement of the Gottfried integral is discussed. The agreement between the E866 results and models employing virtual mesons indicates these non-perturbative processes play an important role in the origin of the $\bar{d}, \bar{u}$ asymmetry in the nucleon sea.

13.85.Qk; 14.20.Dh; 24.85.+p; 14.65.Bt

Recent measurements [1–3] have revealed a marked asymmetry in the distributions of up and down quarks in the nucleon sea. While no known symmetry requires $\bar{u}$ to equal $\bar{d}$, a large $\bar{d}/\bar{u}$ asymmetry was not anticipated. The principal reason for expecting symmetry between up and down quarks in the sea is an assumption that the sea originates primarily from q-$\bar{q}$ pairs produced from gluons. As the masses of the up and down quarks are small compared to the confinement scale, nearly equal numbers of up and down pairs should result. Indeed, a theoretical investigation [4] of the light-quark asymmetry in the nucleon concluded that perturbative processes do not give rise to asymmetries in the up, down sea exceeding 1%. Thus a large $\bar{d}/\bar{u}$ asymmetry requires a non-perturbative origin for an appreciable fraction of these light antiquarks. This paper draws together several implications arising from this observed $\bar{d}/\bar{u}$ asymmetry – the effect of these measurements on existing parton distributions, an examination of the compatibility of the measurements of this asymmetry, and the origin of the effect.

The issue of the equality of $\bar{u}$ and $\bar{d}$ was first encountered in measurements of the Gottfried integral [5], defined as

$$I_G = \int_0^1 \left[F_2^p(x,Q^2) - F_2^n(x,Q^2)\right]/x \; dx, \qquad (1)$$

where F_2^p and F_2^n are the proton and neutron structure functions measured in deep inelastic scattering (DIS) experiments. I_G can be expressed in terms of the valence and sea quark distributions of the proton as:

$$I_G = \frac{1}{3}\int_0^1 \left[u_v(x,Q^2) - d_v(x,Q^2)\right] dx + \tfrac{2}{3}\int_0^1 \left[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)\right] dx. \qquad (2)$$

Under the assumption of a $\bar{u}$, $\bar{d}$ flavor-symmetric sea in the nucleon, the Gottfried Sum Rule (GSR) [5], $I_G = 1/3$, is obtained. Measurements of muon DIS on hydrogen and deuterium by the New Muon Collaboration (NMC) determined that $\int_{0.004}^{0.8} [F_2^p(x) - F_2^n(x)]/x \; dx = 0.221 \pm 0.021$ at $Q^2 = 4$ GeV^2 [1]. Extrapolating to $x = 0$ through the unmeasured small-x region, the Gottfried integral is projected to be 0.235 ± 0.026, significantly below 1/3.

Although the violation of the GSR observed by NMC can be explained by assuming pathological behavior of the parton distributions at $x < 0.004$, a more natural explanation is to abandon the assumption $\bar{u} = \bar{d}$. Specifically, the NMC result implies

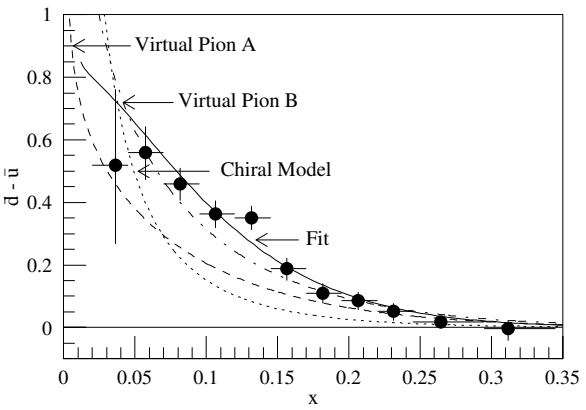

FIG. 1. Comparison of the E866 $\bar{d} - \bar{u}$ results at $Q = 7.35$ GeV with the predictions of various models as described in the text.

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.148 \pm 0.039. \quad (3)$$

The Fermilab E866 measurement [3] of the ratio of Drell-Yan [6] yields from hydrogen and deuterium directly determines the ratio $\bar{d}(x)/\bar{u}(x)$ for $0.02 < x < 0.345$. An excess of $\bar{d}$ over $\bar{u}$ is found over this x range, supporting the observation by NMC that the GSR is violated.

The $\bar{d}/\bar{u}$ ratios measured in E866, together with the CTEQ4M [7] values for $\bar{d} + \bar{u}$, were used to obtain $\bar{d} - \bar{u}$ over the region $0.02 < x < 0.345$ (Fig. 1). As a flavor non-singlet quantity, $\bar{d}(x) - \bar{u}(x)$ has the property that its integral is Q^2-independent [8]. Furthermore, it is a direct measure of the contribution from non-perturbative processes, since perturbative processes cannot cause a significant $\bar{d}$, $\bar{u}$ difference. As shown in Fig. 1, the x dependence of $\bar{d} - \bar{u}$ at $Q = 7.35$ GeV can be approximately parametrized as $0.05x^{-0.5}(1-x)^{14}(1+100x)$.

Integrating $\bar{d}(x) - \bar{u}(x)$ from E866, one finds

$$\int_{0.02}^{0.345} \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.068 \pm 0.007(\text{stat.}) \pm 0.008(\text{syst.}) \quad (4)$$

at $Q = 7.35$ GeV [3]. To investigate the compatibility of this result with the NMC measurement (Eq. 3), the contributions to the integral from the regions $x < 0.02$ and $x > 0.345$ must be estimated. Table I lists the values for the integral of $\bar{d} - \bar{u}$ over the three regions of x for three different parton distribution function (PDF) parametrizations at $Q = 7.35$ GeV. For $x > 0.345$, the contribution to the integral is small (less than 2%). The three parametrizations predict that the bulk of the contribution to the integral comes from $0.02 < x < 0.345$. Since CTEQ4M provides a reasonable description of the E866 data in the low-x region [3], and the contribution from the high-x region is small, we have used CTEQ4M to estimate the contributions to the integral from the unmeasured x regions. This procedure results in a value

TABLE I. Values for $\int \left[\bar{d}(x) - \bar{u}(x)\right] dx$ over various x ranges, evaluated at $Q = 7.35$ GeV, for various PDF parametrizations. Values deduced from E866 are also listed.

x range	CTEQ4M	MRS(R2)	GRV94 [9]	E866
0.345 - 1.0	0.00192	0.00137	0.00148	
0.02 - 0.345	0.0765	0.1011	0.1027	0.068 ± 0.011
0.0 - 0.02	0.0296	0.0588	0.0584	
0.0 - 1.0	0.1080	0.1612	0.1625	0.100 ± 0.018

$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.100 \pm 0.007 \pm 0.017$, which is 2/3 the value deduced by NMC. The systematic error includes the uncertainty (± 0.015) due to the unmeasured x regions, estimated from the variation between CTEQ4M and MRS(R2) [10]. This result is consistent with the integral of the parametrized fit shown in Fig. 1.

The difference between the NMC and E866 results for the $\bar{d} - \bar{u}$ integral raises the question of the compatibility of the two measurements. Figure 2 shows the NMC data for $F_2^p - F_2^n$ at $Q = 2$ GeV, together with the fits of MRS(R2) and CTEQ4M. Both PDF parametrizations give very similar results for $F_2^p - F_2^n$. However, their agreement with the NMC data is poor, especially in the region $0.15 < x < 0.4$. It is instructive to decompose $F_2^p(x) - F_2^n(x)$ into contributions from valence and sea quarks:

$$F_2^p(x) - F_2^n(x) = \tfrac{1}{3}x\left[u_v(x) - d_v(x)\right] + \tfrac{2}{3}x\left[\bar{u}(x) - \bar{d}(x)\right]. \quad (5)$$

Two PDF parametrizations of these contributions are shown in Fig. 2. The valence contribution is positive, while the contribution from the sea is negative. The MRS(R2) and CTEQ4M parametrizations give noticeably different values for the valence and sea contributions, though their net results for $F_2^p - F_2^n$ are very similar. As shown in Fig. 2, the E866 data provide a direct determination of the sea-quark contribution to $F_2^p - F_2^n$, and can be used to distinguish between different PDF parametrizations that produce similar fits to the NMC data. As the direct determination of $\bar{d}(x) - \bar{u}(x)$ is smaller than obtained from either PDF set, the parameters must be adjusted to reduce the magnitude of both the sea and valence distributions in the interval $0.03 \leq x \leq 0.3$. This reduction will force an increase in the valence contribution to the integral from $x \leq 0.03$ and could therefore bring the results from E866 and NMC into better accord. Fig. 2 also suggests that the reason for the difference between the PDF fits and the NMC results in the interval $0.15 < x < 0.4$ is that the PDFs cannot accommodate the rapid variation in the asymmetry of the nucleon sea as a function of x revealed by E866.

The E866 data also allow the first determination of the momentum fraction carried by the difference of $\bar{d}$ and $\bar{u}$. We obtain $\int_{0.02}^{0.345} x\left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.0065 \pm 0.0010$ at $Q = 7.35$ GeV. If CTEQ4M is used to estimate the

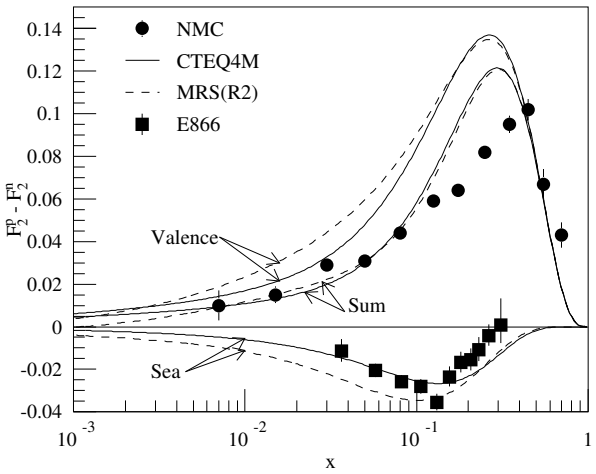

FIG. 2. $F_2^p - F_2^n$ as measured by NMC at $Q = 2$ GeV compared with predictions based on the CTEQ4M and MRS(R2) parametrizations. Also shown are the E866 results, evolved to $Q = 2$ GeV, for the sea-quark contribution to $F_2^p - F_2^n$. For each prediction, the top (bottom) curve is the valence (sea) contribution and the middle curve is the sum of the two.

contributions from the unmeasured x regions, one finds that $\int_0^1 x\left[\bar{d}(x) - \bar{u}(x)\right] dx = 0.0075 \pm 0.0011$, roughly 3/4 of the value obtained from the PDF parametrizations. Unlike the integral of $\bar{d}(x) - \bar{u}(x)$, the momentum integral is Q^2-dependent and decreases as Q^2 increases.

We now turn to the origin of the $\bar{d}/\bar{u}$ asymmetry. As early as 1982, Thomas [11] pointed out that the virtual pions that dress the proton will lead to an enhancement of $\bar{d}$ relative to $\bar{u}$ via the (non-perturbative) "Sullivan process." Sullivan [12] previously showed that in DIS these virtual mesons scale in the Bjorken limit and contribute to the nucleon structure function. Following the publication of the NMC result, many papers [13-20] have treated virtual mesons as the origin of the asymmetry in the up, down sea of the nucleon.

Using the notion that the physical proton (p) may be expanded in a sum of products of its virtual meson-baryon (MB) states, one writes $p = (1-\alpha)p_0 + \alpha\mathrm{MB}$, where α is the probability of the proton being in virtual states MB and p_0 is a proton configuration with a symmetric sea. It is easy to show [14,18] that

$$\int_0^1 \left[\bar{d}(x,Q^2) - \bar{u}(x,Q^2)\right] dx = (2a - b)/3 \qquad (6)$$

where a is the probability of the virtual state πN and b the probability for $\pi\Delta$. These two configurations are the dominant intermediate MB states contributing to the asymmetry [18,19]. Further, most recent calculations of the relative probability of these two configurations find $a \approx 2b$ [18,19]. Using the value for the integral extracted from E866 and assuming $a = 2b$ yields $a = 2b = 0.20 \pm 0.036$, requiring a substantial presence of virtual mesons in the nucleon in this model.

Following the observation [17,21] that virtual pion configurations affect the spin structure of the nucleon because pion emission induces spin flip, it can be shown that

$$\begin{aligned} g_A &= \Delta u_p - \Delta d_p \\ &= \frac{5}{3} - \frac{20}{27}(2a + b) + \frac{32}{27}\sqrt{2ab} \\ &= 1.53 \pm 0.024 \end{aligned} \qquad (7)$$

using the above values of a and b determined from the E866 result. Here Δu_p (Δd_p) is the total spin carried by the up (down) quarks in the proton. The resulting value for g_A is reduced from the simple SU(6) value of 5/3, and is near the value (1.51) calculated by Weinberg [22] who used chiral perturbation theory to calculate the effect of virtual pions. However these results are far from the measured value of $g_A = 1.260 \pm 0.003$ [23]. Presumably relativistic effects [21] quench the spin of the constituent quarks allowing better agreement with experiment.

The x dependences of $\bar{d} - \bar{u}$ and $\bar{d}/\bar{u}$ obtained in E866 provide important constraints for theoretical models. Fig. 1 compares $\bar{d}(x) - \bar{u}(x)$ from E866 with a virtual-pion model calculation following the procedure detailed by Kumano [14]. Since the E866 results are shown at a Q of 7.35 GeV, the SMRS(P2) [24] parametrization for the pion structure functions at this Q is employed. The curve labeled "virtual pion A" in Fig. 1 uses a dipole form with $\Lambda = 1.0$ GeV for the πNN and $\pi N\Delta$ form factors, and is seen to underpredict the magnitude of $\bar{d} - \bar{u}$. However as has been noted [18,19], Δ production experiments [25] suggest a considerably softer form factor for $\pi N\Delta$ than for πNN. Indeed much better agreement with the E866 results is obtained by reducing Λ for the $\pi N\Delta$ form factor to 0.8 GeV, as shown by the curve labeled "virtual pion B" in Fig. 1. This fit produces a value of 0.11 for the integral of $\bar{d} - \bar{u}$ and 1.52 for g_A. If Λ is chosen to be 0.9 GeV (0.7 GeV) for the πNN ($\pi N\Delta$) form factor, one finds nearly exact accord with the values cited in the previous paragraph.

A different approach for including the effects of virtual mesons has been presented by Eichten, Hinchliffe, and Quigg [17] and further investigated by Szczurek *et al.* [20]. In the framework of chiral perturbation theory, the relevant degrees of freedom are constituent quarks, gluons, and Goldstone bosons. In this model, a portion of the sea comes from the couplings of Goldstone bosons to the constituent quarks, such as $u \to d\pi^+$ and $d \to u\pi^-$. The excess of $\bar{d}$ over $\bar{u}$ is then simply due to the additional up valence quark in the proton. The predicted $\bar{d} - \bar{u}$ from the chiral model is shown in Fig. 1 as the dotted curve. We follow the formulation of Szczurek *et al.* [20] to calculate $\bar{d}(x) - \bar{u}(x)$ at $Q = 0.5$ GeV, and then evolve the results to $Q = 7.35$ GeV. In the chiral model, the mean-x of $\bar{d} - \bar{u}$ is considerably lower than in the virtual-pion

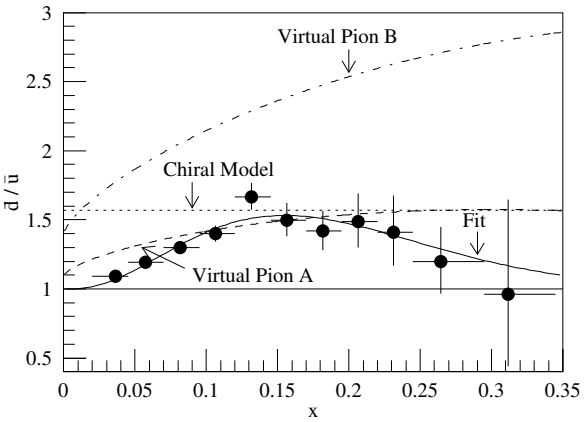

FIG. 3. Comparison of E866 $\bar{d}/\bar{u}$ ratios at $Q = 7.35$ GeV with the predictions of two virtual pion models and the chiral model. The fit $1 + 1120x^{2.75}(1-x)^{15}$ is also shown.

model just considered. This difference reflects the fact that the pions are softer in the chiral model, since they are coupled to constituent quarks which on average carry only 1/3 of the nucleon momentum. The x dependence of the E866 data favors the virtual-pion model over the chiral model, suggesting that correlations between the chiral constituents should be taken into account.

Another non-perturbative process that can produce a $\bar{d}$, $\bar{u}$ asymmetry is the coupling of instantons to the valence quarks. An earlier publication [26] presented an asymmetry due to instantons but parametrized the result in terms of the asymmetry observed in NMC, and therefore has no independent predictive power. Also the *ad hoc* x dependence used for $\bar{d}(x)/\bar{u}(x)$ is in poor agreement with the E866 result. We are unable to determine if better agreement with data can be obtained by an improved parametrization within the instanton model.

It is also instructive to compare the model predictions of $\bar{d}(x)/\bar{u}(x)$ with the E866 results. Figure 3 shows that the two virtual-pion models and the chiral model give $\bar{d}(x)/\bar{u}(x)$ values very different from the E866 result. Note that these calculations do not include the perturbative processes $g \to u\bar{u}, d\bar{d}$ which generate a symmetric sea. Indeed, the $\bar{d}/\bar{u}$ data provide valuable information on the relative importance of the perturbative (symmetric) versus the non-perturbative sea. In the absence of a symmetric sea, the chiral model predicts a $\bar{d}/\bar{u}$ ratio of 11/7 for all x. Figure 3 shows that the observed ratio nearly equals this value for $0.1 < x < 0.2$, leaving little room for any perturbatively generated symmetric sea in this interval, which seems unreasonable. The same problem also arises for the virtual-pion model A. In contrast, the virtual-pion model B readily accommodates contributions from a symmetric sea.

In summary, E866 has provided the first determination of $\bar{d}/\bar{u}$, $\bar{d} - \bar{u}$, and the integral of $\bar{d} - \bar{u}$ over the range $0.02 \leq x \leq 0.345$. It provides an independent confirmation of the violation of the Gottfried Sum Rule reported from DIS experiments. The magnitude of the integral of $\bar{d} - \bar{u}$ over the region $0.02 < x < 0.345$ is smaller than obtained from some current PDF parametrizations. This indicates that the violation of the Gottfried Sum Rule is likely smaller than reported by NMC. Together with the NMC data, the E866 results impose stringent constraints on both sea- and valence-quark distributions. The good agreement between the E866 $\bar{d} - \bar{u}$ data and the virtual-pion model indicates that virtual meson-baryon components play an important role in determining non-singlet structure functions of the nucleon. Future experiments extending the measurements of $\bar{d}/\bar{u}$ to other x and Q^2 regions can further illuminate the interplay between the perturbative and non-perturbative elements of the nucleon sea.

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