The Flavor Asymmetry of the Light Quark Sea from Semi-inclusive Deep-inelastic Scattering

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The flavor asymmetry of the light quark sea of the nucleon is determined in the kinematic range $0.02 < x < 0.3$ and $1\ \mathrm{GeV}^2 < Q^2 < 10\ \mathrm{GeV}^2$, for the first time from semi-inclusive deep-inelastic scattering. The quantity $(\overline{d}(x) - \overline{u}(x))/(u(x) - d(x))$ is derived from a relationship between the yields of positive and negative pions from unpolarized hydrogen and deuterium targets. The flavor asymmetry $\overline{d} - \overline{u}$ is found to be non-zero and x dependent, showing an excess of $\overline{d}$ over $\overline{u}$ quarks in the proton.

The flavor content of the nucleon sea has come to be recognized as an important domain for testing models of nucleon structure[1]. Until recently there has been little experimental constraint on the flavor asymmetry in the quark distributions of the light sea quarks in the nucleon. The first was an integral test, based on a comparison of inclusive deep-inelastic scattering on the proton and the neutron to determine the Gottfried Sum [2] defined as

$$S_G \equiv \int_0^1 \frac{dx}{x} \left(F_2^p(x) - F_2^n(x)\right), \qquad (1)$$

where $F_2^p(x)$ and $F_2^n(x)$ are the structure functions of the proton and neutron, respectively. A flavor symmetric sea, $\overline{u}(x) = \overline{d}(x)$, leads to the Gottfried Sum Rule $S_G = 1/3$. A measurement of the Gottfried Sum by NMC [3] resulted in $S_G = 0.235 \pm 0.026$, at $Q^2 = 4\ \mathrm{GeV}^2$. If isospin symmetry holds, a global flavor asymmetry $\int_0^1 (\overline{d}(x) - \overline{u}(x))dx \approx 0.15$ would account for the NMC result. Many ideas such as Pauli blocking and pion clouds have been proposed to explain such a flavor asymmetry in the sea[1]. Two methods have been proposed to measure its x dependence: the Drell-Yan process [4] and semi-inclusive deep inelastic scattering [5].

Results are presented here for the x dependence of $(\overline{d} - \overline{u})/(u - d)$ from the analysis of charged pion yields in semi-inclusive deep-inelastic scattering of positrons on unpolarized hydrogen and deuterium targets. More details are given in ref. [6]. The data cover the kinematic range $0.02 < x < 0.3$ and $1\ \mathrm{GeV}^2 < Q^2 < 10\,\mathrm{GeV}^2$, where $-Q^2$ is the four-momentum transfer squared of the exchanged virtual photon and $x = Q^2/(2M\nu)$ is the Bjorken variable with M being the proton mass, $\nu = E - E'$ the virtual photon energy, and $E(E')$ the energy of the incident (scattered) positron.

The ratio $(\overline{d} - \overline{u})/(u - d)$ is determined from a quantity that combines good sensitivity to the sea asymmetry with minimal sensitivity to instrumental effects [5]:

$$r(x,z) = \frac{N_p^{\pi^-}(x,z) - N_n^{\pi^-}(x,z)}{N_p^{\pi^+}(x,z) - N_n^{\pi^+}(x,z)}, \qquad (2)$$

where $z = E^\pi/\nu$ is the fraction of the virtual photon energy carried by the pion and $N^\pi(x,z)$ is the yield of pions coming from deep-inelastic scattering off nucleons. Factorization between the hard scattering process and the hadronization of the struck quark implies

$$N^{\pi^\pm}(x,z) \quad \propto \qquad (3)$$

$$\sum_i e_i^2 \left[q_i(x) D_{q_i}^{\pi^\pm}(z) + \overline{q}_i(x) D_{\overline{q}_i}^{\pi^\pm}(z)\right], \qquad (4)$$

where e_i is the quark charge in units of the elementary charge, $q_i(x)$ and $\overline{q}_i(x)$ are the density distributions of quarks and antiquarks of flavor i, and the fragmentation functions $D_{q_i}^{\pi^\pm}(z)$ represent the probability that the quark of flavor i fragments to a charged pion. Assuming isospin symmetry between protons and neutrons as well

as charge conjugation invariance, the number of light quark fragmentation functions is reduced to two: the favored and disfavored fragmentation functions [7], e.g. $D_u^{\pi^+}$ and $D_u^{\pi^-}$. Using Eq.(4) to express $r(x,z)$ in terms of quark distributions and fragmentation functions results in:

$$\frac{1+r(x,z)}{1-r(x,z)} = \frac{u(x)-d(x)+\overline{u}(x)-\overline{d}(x)}{(u(x)-\overline{u}(x))-(d(x)-\overline{d}(x))}J(z), \quad (5)\text{–}(6)$$

where $J(z) = \frac{3}{5}\left(\frac{1+D'(z)}{1-D'(z)}\right)$ and $D' = D_u^{\pi^-}/D_u^{\pi^+}$. It should be noted that the right-hand side of Eq.(6) factorizes into two independent functions of x and z respectively. Thus, the equation may be rearranged to isolate a quantity sensitive to the flavor asymmetry:

$$\frac{\overline{d}(x)-\overline{u}(x)}{u(x)-d(x)} = \frac{J(z)[1-r(x,z)]-[1+r(x,z)]}{J(z)[1-r(x,z)]+[1+r(x,z)]}. \quad (7)\text{–}(8)$$

The assumptions leading to Eq.(6) imply that the right side of Eq.(8) is independent of z.

In the HERMES experiment, 27.5 GeV positrons circulating in the HERA storage ring at DESY are scattered on internal H_2, D_2, and ^{3}He targets. The target gas is fed into the center of a 40-cm-long open-ended storage cell. Systematic uncertainties are minimized by cycling the three gases through one of various permutations, several times during each 8-12 hour HERA fill. The unpolarized luminosity of $(1-5)\times10^{32}$ cm^{-2}s^{-1} is monitored by a pair of $NaBi(WO_4)_2$ electromagnetic calorimeters that detect Bhabha scattering from target electrons.

A detailed description of the HERMES spectrometer is provided elsewhere [8]. One of the features of the spectrometer central to this work is its threshold Čerenkov counter, which distinguishes pions from heavier hadrons for particles with momenta greater than 3.8 GeV while maintaining better than 95% pion identification efficiency at momenta larger than 6 GeV.

The kinematic requirements used in this analysis are $Q^2 > 1$ GeV^2, invariant mass W of the initial photon-nucleon system greater than 2 GeV, and fractional energy $y = \nu/E$ of the incident lepton transferred to the virtual photon less than 0.85. Events are required to originate from the target-beam interaction region. For the determination of $r(x,z)$, the data are partitioned in five bins of x in the range $0.02 < x < 0.3$ and up to six bins in z in the range $0.2 < z < 0.8$. The pions are selected to be in the current fragmentation region (i.e. derived from the struck quark and not target fragments) by requiring $x_F = 2P_L/W$ to be greater than 0.25, where P_L is the momentum component of the pion in the longitudinal direction with respect to the virtual photon in the photon-nucleon center-of-mass frame. Data at Bjorken $x > 0.3$ are excluded because they are dominated by scattering from the valence quarks. The yields for the neutron target appearing in Eq.(2) can be inferred from yields obtained from deuterium and hydrogen targets, $N_n^{\pi^\pm} = N_d^{\pi^\pm} - N_p^{\pi^\pm}$. The fragmentation functions $D_{q_i}^{\pi^\pm}(z)$ and their ratio $D'(z)$ were extracted from the measured pion yields from a ^{3}He target [9], using Eq.(4) together with the GRV 94 LO [10] parameterization of parton distributions.

The results for the quantity $(\overline{d}-\overline{u})/(u-d)$ show no z dependence in each x bin, and are consistent with the form of factorization shown in Eq. (6). The values of $(\overline{d}-\overline{u})/(u-d)$ averaged over z are plotted in Fig. 1(a) as a function of x. They are non-zero and positive everywhere in the measured x region, clearly showing an excess of $\overline{d}$ quarks over $\overline{u}$ quarks in the proton. Also included in this figure are the GRV 94 LO [10], CTEQ 4lq [12], MRS (A) [13] low Q^2, and MRST (98) [14] parameterizations of $(\overline{d}-\overline{u})/(u-d)$, calculated at the average Q^2 of the events in each x bin. The HERMES results are determined without making higher order QCD corrections and so only leading order parameterizations should be compared to them. At low Q^2, only GRV 94 is available at leading order. The distribution $\overline{d}-\overline{u}$ as a function of x is thus derived from $(\overline{d}-\overline{u})/(u-d)$ using the GRV 94 LO parameterization of $u(x)-d(x)$, again calculated at the appropriate Q^2 for each x bin. The results are presented in Fig. 1(b), and give an integral over the measured x region of $\int_{0.02}^{0.3}(\overline{d}(x)-\overline{u}(x))dx =$

$0.107 \pm 0.021(\text{stat}) \pm 0.017(\text{sys})$, after the integrand at each x bin is 'evolved' to the average measured Q_o^2 of 2.3 GeV^2 by applying the ratio of the GRV 94 values for $\overline{d} - \overline{u}$ at the two values of Q^2. The GRV 94 LO parameterization is used to estimate the portion of the integral in the unmeasured regions. The contribution from $x < 0.02$ is significant: 0.050 (almost 50% of that over the measured x range), while the high x region $x > 0.3$ contributes only 0.006. Including an extrapolation uncertainty estimate based on differences among the available parameterizations, the total integral over all x is then approximately 0.16 ± 0.03, which is consistent with the results first seen by NMC[3].

An alternate approach to the measurement of the flavor asymmetry is the comparison of the Drell-Yan process on protons and deuterons, which is sensitive to the quantity $\overline{u}/\overline{d}$ [4]. The E866 collaboration at Fermilab recently reported a measurement of the flavor asymmetry in the x range $0.02 < x < 0.345$ [15]. E866 uses the CTEQ 4M [12] parameterization of $\overline{u} + \overline{d}$ to extract $\overline{d} - \overline{u}$ from the measured quantity $\overline{d}/\overline{u}$. These results given at a Q_o^2 of 54 GeV^2 are included in Fig. 1(b). The sea asymmetries measured in deep-inelastic scattering and in Drell-Yan experiments agree, even though the Q^2 of the two experiments differ by a factor of about 20.

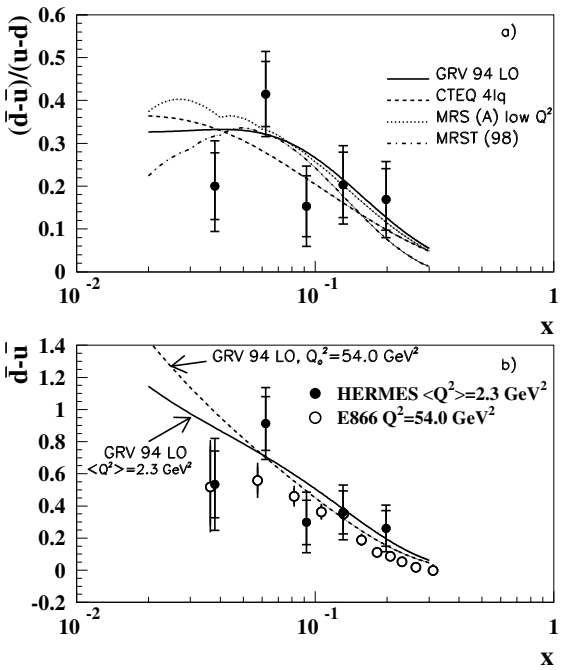

Figure 1. (a) $(\overline{d} - \overline{u})/(u - d)$ as a function of x. The curves are the GRV 94 LO [10], CTEQ 4lq [12], MRS (A) [13] low Q^2, and MRST (98) [14] parameterizations calculated at the appropriate Q^2 for each x-bin. (b) $\overline{d} - \overline{u}$ as a function of x. The open circles are the E866 [15] results for $\overline{d} - \overline{u}$ at Q_0^2=54 GeV^2. The solid (dashed) curve is the GRV 94 LO [10] parameterization, evaluated at the HERMES (E866) Q_0^2 values.

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