Evidence for Substantial Charge Symmetry Violation in Parton Distributions

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Charge symmetry for parton distributions can be tested by comparing structure functions from neutrino and charged lepton deep inelastic scattering. New experiments provide rather tight upper limits on parton charge symmetry violation (CSV) for intermediate x, but suggest CSV effects at small x. Careful study of several corrections fails to remove this low-x discrepancy. We are thus forced to consider surprisingly large CSV effects in nucleon sea distributions. [S0031-9007(98)07546-2]

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In nuclear physics charge symmetry, which interchanges protons and neutrons (simultaneously interchanging up and down quarks), is respected to a high degree of precision. Most low-energy tests of charge symmetry find that it is good to at least 1% in reaction amplitudes [1]. Therefore, charge symmetry is usually assumed to be valid in discussions of strong interactions. Currently all phenomenological analyses describe deep inelastic scattering (DIS) data using charge symmetric parton distributions. Until recently this assumption seemed to be justified, since high-energy experimental data were consistent with parton charge symmetry [2].

Experimental verification of charge symmetry is difficult, partly because charge symmetry violation (CSV) effects are expected to be small, and partly because CSV often mixes with parton flavor symmetry violation (FSV). Experimental measurements by the New Muon Collaboration (NMC) [3] have been widely interpreted as evidence for what is termed SU(2) FSV. Recent measurements of the ratio of Drell-Yan cross sections in pp and pD scattering [4,5] also indicate substantial FSV. However, as pointed out by Ma [6], all these experiments could be explained by sufficiently large CSV effects, even in the limit of exact flavor symmetry. In view of these ambiguities in the interpretation of experimental data, it would be highly desirable to have experiments which separate CSV from FSV.

Charge symmetry implies the equivalence between up (down) quark distributions in the proton and down (up) quarks in the neutron. We define charge symmetry violating distributions

$$\begin{aligned} \delta u(x) &= u^p(x) - d^n(x), \\ \delta d(x) &= d^p(x) - u^n(x), \end{aligned} \tag{1}$$

where the superscripts p and n refer to the proton and neutron, respectively (quark distributions without subscripts will refer to the proton). The relations for CSV in antiquark distributions are analogous.

In the quark-parton model the structure functions of concern to us, which are measured in neutrino, antineutrino, and charged lepton DIS on an isoscalar target N_0, are given in terms of parton distribution functions and CSV terms [2]

$$\begin{aligned} F_2^{\nu N_0}(x,Q^2) &= x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + 2s(x) + 2\bar{c}(x) - \delta u(x) - \delta\bar{d}(x)], \\ F_2^{\bar{\nu} N_0}(x,Q^2) &= x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + 2\bar{s}(x) + 2c(x) - \delta d(x) - \delta\bar{u}(x)], \\ F_2^{l N_0}(x,Q^2) &= \frac{5}{18}x\Big\{u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + \frac{2}{5}[s(x) + \bar{s}(x)] + \frac{8}{5}[c(x) + \bar{c}(x)] \\ &\qquad - \frac{4}{5}[\delta d(x) + \delta\bar{d}(x)] - \frac{1}{5}[\delta u(x) + \delta\bar{u}(x)]\Big\}. \end{aligned} \tag{2}$$

The best test of CSV to date is the "charge ratio," which relates the neutrino structure function to the structure function measured in charged lepton DIS

$$\begin{aligned} R_c(x) &\equiv \frac{F_2^{\mu N_0}(x)}{\frac{5}{18}F_2^{\nu N_0}(x) - x[s(x) + \bar{s}(x)]/6} \\ &\approx 1 - \frac{s(x) - \bar{s}(x)}{\overline{Q}(x)} \\ &\quad + \frac{4\delta u(x) - \delta\bar{u}(x) - 4\delta d(x) + \delta\bar{d}(x)}{5\overline{Q}(x)}. \end{aligned} \tag{3}$$

In Eq. (3), $\bar{Q}(x) \equiv \sum_{q=u,d,s}[q(x) + \bar{q}(x)] - 3[s(x) + \bar{s}(x)]/5$, and we expand to lowest order in small quantities. A deviation $R_c(x) \neq 1$, at any value of x, must arise either from CSV effects or from $s(x) \neq \bar{s}(x)$.

Recent experimental measurements allow a precise comparison between $F_2^\nu(x,Q^2)$ and $F_2^\mu(x,Q^2)$. The CCFR Collaboration compared the structure function $F_2^\nu(x,Q^2)$ from their ν-Fe data [7] with $F_2^\mu(x,Q^2)$ from μ-D measurements by NMC [8]. In the region of intermediate values of Bjorken x ($0.1 \leq x \leq 0.4$), the two structure functions are in very good agreement, giving upper limits of a few percent on parton CSV contributions. In the small x region, however ($x < 0.1$), the two structure functions differ by as much as 10–15%. This can be seen in Fig. 1 where the "charge ratio" was obtained by integrating over the region of overlap in Q^2 of the two experiments. The data points in Fig. 1 represent different ways of calculating nuclear shadowing corrections, as we will discuss. Several corrections must be applied to the data before any conclusions may be drawn from this discrepancy. The CCFR Collaboration made a careful study of overall normalization, charm threshold, and isoscalar correction effects [7]. Here we discuss the most important remaining effects, nuclear corrections for neutrinos and $s(x) \neq \bar{s}(x)$ effects.

Heavy target corrections for neutrinos (nuclear European Muon Collaboration effect, shadowing, and antishadowing) are generally calculated using correction factors from charged lepton reactions at the same kinematic values. *A priori*, there is no reason that neutrino and charged lepton heavy target corrections should be identical, especially if such corrections depend strongly on the properties of the exchanged object (photon, W) used to probe the structure of the target. Since this is the case for nuclear shadowing corrections in the small x_B region for small to moderately large Q^2 values, we reexamined shadowing corrections to neutrino DIS, focusing on the differences between neutrino and charge lepton scattering and on effects due to the Q^2 dependence of shadowing. This work will be published elsewhere [9]. We used a two-phase model which has been successfully applied to the description of shadowing in charged lepton DIS [10].

In generalizing this approach to weak currents, subtle differences between shadowing in neutrino and charged lepton DIS arise because of the partial conservation of axial currents (PCAC) and the coupling of the weak current to both vector and axial vector mesons. For the axial current, PCAC requires that shadowing in neutrino scattering for low Q^2 ($\approx m_\pi^2$) is determined by the absorption of pions on the target [11], while at larger Q^2 values axial vector mesons ($a_1^+ \ldots$ for W^+) become important. For the weak vector current one must include vector mesons $\rho^+ \ldots$. Since the coupling constants are related by $f_{\rho^+}^2 = f_{a_1}^2 = 2f_{\rho^0}^2$ and the structure functions by $F_2^\nu \approx \frac{18}{5}F_2^\mu$, the *relative* shadowing due to vector meson dominance in neutrino DIS is roughly half of that in charged lepton DIS. For large Q^2 values, shadowing due to Pomeron exchange (which is of leading twist) becomes dominant, leading to identical (relative) shadowing in neutrino and charged lepton DIS.

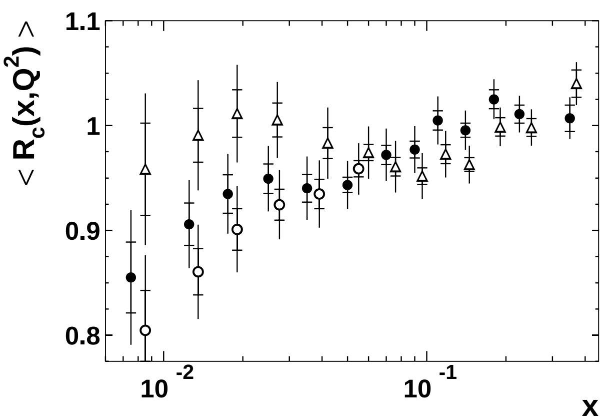

FIG. 1. The "charge ratio" R_c of Eq. (3) vs x calculated using CCFR [7] data for neutrino and NMC [3] data for muon structure functions. Open triangles: no heavy target corrections; open circles: ν data corrected for heavy target effects using corrections from charged lepton scattering; solid circles: ν shadowing corrections calculated in the "two-phase" model. Both statistical and systematic errors are shown.

Using this two-phase model, we calculated shadowing corrections to the CCFR ν and used these corrections in calculating the charge ratio R_c of Eq. (3). There are also nuclear effects in the deuteron. However, because of the low density of the deuteron, these are (relatively speaking) very small and have a negligible effect on the charge ratio [19]. We integrated the structure functions above $Q^2 = 3.2$ GeV^2 in the overlapping kinematic region of the two experiments and used a parametrization of the nuclear corrections in charged lepton DIS to correct the data in the nonshadowing region. The result is shown in Fig. 1. The open triangles show the charge ratio with no ν shadowing. The open circles show the charge ratio with heavy target corrections taken from charged lepton reactions, and the solid circles show the shadowing using our two-phase model. At small x, careful consideration of neutrino shadowing corrections decreases, but does not resolve, the low-x discrepancy between the CCFR and NMC data.

The structure function $F_2^{\rm CCFR}$ is a flux weighted average between ν and $\bar{\nu}$ structure functions [7]. This becomes important if charge symmetry is violated or if $s(x) \neq \bar{s}(x)$. If we define $\alpha = \Phi_\nu/(\Phi_\nu + \Phi_{\bar{\nu}})$, where Φ_ν and $\Phi_{\bar{\nu}}$ are the ν and $\bar{\nu}$ fluxes, respectively, $F_2^{\rm CCFR}(x,Q^2)$ is proportional to

$$F_2^{\rm CCFR}(x,Q^2) = \alpha F_2^\nu(x,Q^2) + (1-\alpha)F_2^{\bar{\nu}}(x,Q^2)\,. \tag{4}$$

This is equal to $\frac{1}{2}[F_2^\nu(x,Q^2) + F_2^{\bar{\nu}}(x,Q^2)]$ if $\alpha = \frac{1}{2}$ or if the two structure functions are equal. The value of α in the relevant kinematic region is $\approx$0.83 in the CCFR experiment so to a good approximation $F_2^{\rm CCFR}(x,Q^2)$ can be regarded as a neutrino structure function.

The most likely explanation for the small x discrepancy in the charge ratio is either from different strange quark distributions $s(x) \neq \bar{s}(x)$ [12], or from charge symmetry violation. First, we examine the role played by the strange quark distributions. Assuming charge symmetry, $s(x)$ and $\bar{s}(x)$ are given by a linear combination of neutrino and muon structure functions,

$$\frac{5}{6}F_2^{\rm CCFR}(x,Q^2) - 3F_2^{\rm NMC}(x,Q^2) =$$

$$\frac{1}{2}x[s(x) + \bar{s}(x)] + \frac{5}{6}(2\alpha - 1)x[s(x) - \bar{s}(x)]\,. \tag{5}$$

Under the assumption $s(x) = \bar{s}(x)$, this relation could be used to extract the strange quark distribution. However, as is well known, $s(x)$ obtained in this way is inconsistent with results extracted from independent experiments.

Opposite sign dimuon production in deep inelastic ν and $\bar{\nu}$ scattering provides a direct determination of both $s(x)$ and $\bar{s}(x)$. The CCFR Collaboration extracted $s(x)$ and $\bar{s}(x)$ from a next to leading order (NLO) analysis [13] of their dimuon data. The strange and antistrange distributions were equal within experimental errors. However, since the number of antineutrino events is much smaller than that of the neutrino events, the errors of this analysis are inevitably large.

It appears plausible that the low-x discrepancy in the charge ratio of Eq. (3) could be accounted for by allowing $s(x) \neq \bar{s}(x)$. To test this hypothesis we combined the dimuon production data, averaged over ν and $\bar{\nu}$ events, with the structure functions from neutrino and charged lepton scattering [Eq. (5)]. Defining $\alpha' = N_\nu/(N_\nu + N_{\bar{\nu}})$, where $N_\nu = 5030$, $N_{\bar{\nu}} = 1060$ ($\alpha' \approx 0.83$) are, respectively, the ν and $\bar{\nu}$ events from the dimuon production experiment [13], the flux-weighted experimental distribution $xs(x)^{\mu\mu}$ from dimuon production is

$$xs^{\mu\mu}(x) = \frac{1}{2}\,x\,[s(x) + \bar{s}(x)] + \frac{1}{2}\,(2\alpha' - 1)x[s(x) - \bar{s}(x)]. \qquad (6)$$

Equations (5) and (6) form a pair of linear equations which can be solved for $s(x)$ and $\bar{s}(x)$. We can simultaneously test the compatibility of the various experiments.

In Fig. 2 we show the results obtained for $xs(x)$ (open circles) and $x\bar{s}(x)$ (solid circles) by solving the linear equations, Eqs. (5) and (6). Both the structure functions and dimuon data have been integrated over $Q^2 > 3.2\ \mathrm{GeV}^2$ in the overlapping kinematical regions. In averaging the dimuon data, we used the CTEQ4L parametrization for $s^{\mu\mu}(x)$ [14]. The results are completely unphysical, since the equations require $\bar{s}(x) < 0$. Our analysis strongly suggests that requiring charge symmetry, but allowing $s(x) \neq \bar{s}(x)$, cannot resolve the discrepancy between $F_2^{\mathrm{CCFR}}(x, Q^2)$ and $F_2^{\mathrm{NMC}}(x, Q^2)$. The experimental results are incompatible, even if $\bar{s}(x)$ is completely unconstrained [15].

As neither neutrino shadowing corrections nor allowing $s(x) \neq \bar{s}(x)$ removes the low-x discrepancy, there remain two possible explanations. Either one of the experimental structure functions [or $s(x)$] is incorrect at low x, or parton charge symmetry is violated in this region. Assuming the possibility of parton CSV, we can combine the dimuon data for $s(x)$, Eq. (6), with Eq. (5) to obtain

$$\frac{5}{6}\,F_2^{\mathrm{CCFR}}(x, Q^2) - 3F_2^{\mathrm{NMC}}(x, Q^2) - xs^{\mu\mu}(x) \approx \frac{x(2\alpha - 1)}{3}\,[s(x) - \bar{s}(x)] + \frac{1}{2}\,x[\delta\bar{d}(x) - \delta\bar{u}(x)]. \qquad (7)$$

In Eq. (7) we use the experimental value $\alpha = \alpha'$; this equation is valid at small x, where sea quark distributions are much larger than valence quarks, so we make the simplest assumption, namely that $\delta q_v(x) = \delta q(x) - \delta\bar{q}(x) \approx 0$ [16]. (With the present data we cannot separate sea and valence, and this working hypothesis does not affect the conclusion concerning the size of the charge symmetry violation.)

The left-hand side of Eq. (7) is positive. Consequently, the smallest CSV effects will be obtained when $\bar{s}(x) = 0$. In Fig. 3 we show the CSV effects needed to satisfy the experimental values in Eq. (7). The open circles are obtained when we set $\bar{s}(x) = 0$, and the solid circles result from setting $\bar{s}(x) = s(x)$. The CSV effect required to account for the low-x NMC-CCFR discrepancy is extraordinarily large. It is roughly the same size as the

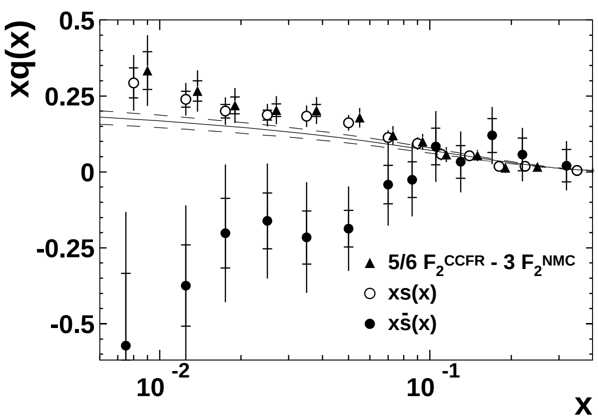

FIG. 2. $xs(x)$ (open circles) and $x\bar{s}(x)$ (solid circles) extracted by combining CCFR and NMC structure functions with $s(x)$ extracted from dimuon experiments, as given in Eqs. (5) and (6). Solid triangles: $\frac{5}{6}F_2^{\mathrm{CCFR}} - 3F_2^{\mathrm{NMC}}$. Solid line: $xs(x)$ from a NLO analysis (Ref. [13]); dashed band indicates $\pm 1\sigma$ uncertainty.

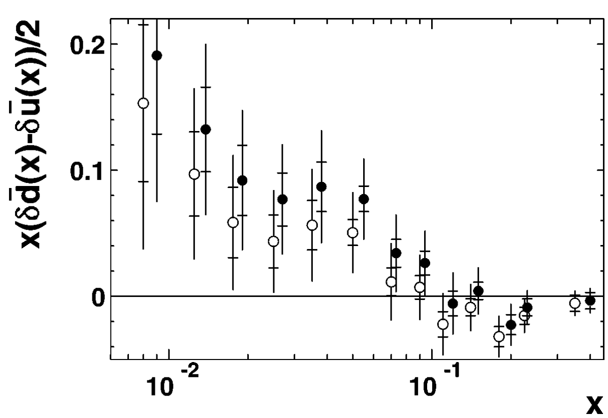

FIG. 3. Charge symmetry violating distributions extracted from the CCFR and NMC structure function data and the CCFR dimuon production data under the assumption that $s(x) = \bar{s}(x)$ (solid circles) and $\bar{s}(x) \approx 0$ (open circles).

strange quark distribution at small x. This CSV term is roughly 25% of the light sea quark distributions for $x < 0.1$, and the sign gives $\overline{d}^p(x) > \overline{u}^n(x)$ and $\overline{d}^n(x) > \overline{u}^p(x)$.

Clearly, CSV effects of this magnitude need further experimental verification. It is hard to imagine how such large CSV effects are compatible with the high precision of charge symmetry measured at low energies. The level of CSV required is surprising, as it is at least 2 orders of magnitude larger than theoretical CSV estimates [17,18]. We will discuss the implications of such a large violation of charge symmetry in a subsequent paper [19]. Theoretical considerations suggest that $\delta\overline{d}(x) \approx -\delta\overline{u}(x)$ [17]; with this sign CSV effects also require large flavor symmetry violation. If CSV effects of this magnitude are really present, then one must include charge symmetry violating quark distributions in phenomenological models from the outset, and reanalyze the extraction of parton distributions.

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