Evidence for Substantial Charge Symmetry Violation in Parton Distributions

C. Boros\textsuperscript{1}, J.T. Londergan\textsuperscript{2} and A.W. Thomas\textsuperscript{1}

\begin{itemize}
\item \textsuperscript{1} Department of Physics and Mathematical Physics, and Special Research Center for the Subatomic Structure of Matter, University of Adelaide, Adelaide 5005, Australia
\item \textsuperscript{2} Department of Physics and Nuclear Theory Center, Indiana University, Bloomington, IN 47404, USA
\end{itemize}

(March 27, 2022)

Abstract

In principle one can test the validity of charge symmetry for parton distributions by comparing structure functions measured in neutrino and charged lepton deep inelastic scattering. New experiments make such tests possible; they provide rather tight upper limits on parton charge symmetry violation [CSV] for intermediate Bjorken $x$, but appear to show evidence for CSV effects at small $x$. We examine two effects which might account for this experimental discrepancy: nuclear shadowing corrections for neutrinos, and strange quark contributions $s(x) \neq \bar{s}(x)$. We show that neither of these two corrections removes the experimental discrepancy between the structure functions. We are therefore forced to consider the possibility of a surprisingly large CSV effect in the nucleon sea quark distributions.

PACS: 13.60.Hb, 13.15.+g, 12.40.Vv, 11.40.Ha
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 the quantitative evidence which could be extracted from high energy experiments, although not particularly precise, was consistent with charge symmetric parton distributions \[2\].

Experimental verification of charge symmetry is difficult, partly because the relative charge symmetry violation (CSV) effects are expected to be small, requiring high precision experiments, and partly because CSV often mixes with parton flavor symmetry violation (FSV). Recent experimental measurements by the NMC Collaboration \[3\], demonstrating the violation of the Gottfried sum rule \[4\], have been widely interpreted as evidence for what is termed SU(2) FSV. The measurement of the ratio of Drell-Yan cross sections in proton-deuteron and proton-proton scattering, first by the NA51-Collaboration at CERN \[5\] and more recently by the E866 experiment at FNAL \[6\], also indicate substantial FSV. However, as pointed out by Ma \[7\], both of these experiments could in principle be explained by sufficiently large CSV effects, even in the limit of exact flavor symmetry. In view of these ambiguities in the interpretation of current experimental data, it would be highly desirable to have experiments which separate CSV from FSV. A few experiments have been already proposed \[8\] and could be carried out in the near future.

At the level of parton distributions 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

\[
\delta u(x) = u^p(x) - d^n(x), \quad \delta d(x) = d^p(x) - u^n(x),
\]

where the superscripts \(p\) and \(n\) refer to quark distributions in the proton and neutron, respectively (quark distributions without subscripts will refer to the proton). The relations for CSV in antiquark distributions are analogous. Exact charge symmetry would require that the quantities \(\delta u(x)\) and \(\delta d(x)\) vanish.

In the quark-parton model the structure functions measured in neutrino, antineutrino and charged lepton DIS on an iso-scalar target, \(N_0\), are given in terms of the parton distribution functions and the charge symmetry violating distributions \[2\]

\[
\begin{align*}
F_2^{\nu N_0}(x, Q^2) &= x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + 2s(x) + 2\bar{c}(x) - \delta u(x) - \delta \bar{d}(x)] \\
F_2^{\bar{\nu} N_0}(x, Q^2) &= x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + 2s(x) + 2c(x) - \delta d(x) - \delta \bar{u}(x)] \\
xF_3^{\nu N_0}(x, Q^2) &= x[u(x) + d(x) - \bar{u}(x) - \bar{d}(x) + 2s(x) - 2\bar{c}(x) - \delta u(x) + \delta \bar{d}(x)] \\
xF_3^{\bar{\nu} N_0}(x, Q^2) &= x[u(x) + d(x) - \bar{u}(x) - \bar{d}(x) - 2s(x) + 2c(x) - \delta d(x) + \delta \bar{u}(x)] \\
F_2^{e N_0}(x, Q^2) &= \frac{5}{18} x[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + \frac{2}{5}(s(x) + \bar{s}(x)) + \frac{8}{5}(c(x) + \bar{c}(x)) \\
&\quad - \frac{4}{5}(\delta d(x) + \delta \bar{d}(x)) - \frac{1}{5}(\delta u(x) + \delta \bar{u}(x))]
\end{align*}
\] (2)
By comparing structure functions measured in neutrino and charged lepton deep inelastic scattering [DIS] on isoscalar targets, it is possible to test parton charge symmetry. An example is the “charge ratio”, which relates the neutrino structure function to the structure function measured in charged lepton DIS

\[ R_c(x) \equiv \frac{5}{18} \frac{F_2^{\mu N_0}(x) - x(s(x) + \bar{s}(x))}{6} \approx 1 - \frac{s(x) - \bar{s}(x)}{Q(x)} + \frac{4\delta u(x) - \delta \bar{u}(x) - 4\delta d(x) + \delta \bar{d}(x)}{5Q(x)}. \]

Here, we defined \( \bar{Q}(x) \equiv \sum_{q=u,d,s} (q(x) + \bar{q}(x)) - 3(s(x) + \bar{s}(x))/5 \), and we have expanded Eq. 3 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 an inequality between strange and anti-strange quark distributions.

Recent experimental measurements make it possible to carry out a precise comparison between \( F_2^\nu(x, Q^2) \) and \( F_2^\mu(x, Q^2) \). The CCFR-Collaboration compared the neutrino structure function \( F_2^\nu(x, Q^2) \) extracted from their data on an iron target [9] with \( F_2^\mu(x, Q^2) \) measured for the deuteron by the NMC Collaboration [10]. In the region of intermediate values of Bjorken \( x \) (0.1 ≤ \( x \) ≤ 0.4), the two structure functions are in very good agreement; in this region we can set upper limits on parton CSV contributions of a few percent. In the small \( x \)-region however (\( x < 0.1 \)), the CCFR group found that the two structure functions differ by as much as 10-15%. This can be seen in Fig.1 where the “charge ratio” has been obtained by integrating over the region of overlap in \( Q^2 \) of the two experiments. The various 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 iso-scalar correction effects [9]. Here we discuss the most important remaining effects, heavy target corrections for the neutrinos and differences between strange and anti-strange quark distributions.

Nuclear shadowing corrections for neutrinos are generally accounted for by using correction factors obtained from charged lepton reactions at the same kinematic values. \( A \ priori \), there is no reason to assume that neutrino and charged lepton heavy target corrections should be identical. We re-examined heavy target corrections to deep-inelastic neutrino scattering, focusing on the differences between neutrino and charge lepton scattering and on effects due to the \( Q^2 \)-dependence of shadowing for moderately large \( Q^2 \). This work will be published elsewhere [11]. We used a two phase model which has been successfully applied to the description of shadowing in charged lepton DIS [12]. In this approach, vector meson dominance was used to describe the low \( Q^2 \) virtual photon or \( W \) interactions, and Pomeron exchange was used for the approximate scaling region. In generalizing this approach to weak currents, the major new features are that the axial-vector current is only partially conserved, and that the weak current couples to axial vector mesons in addition to vector mesons.

Using this two phase model, we calculated the shadowing corrections to the CCFR neutrino data and used these corrections in calculating the charge ratio \( R_c \) of Eq. 3. The result is shown in Fig. 1. The solid triangles show the charge ratio when no shadowing corrections are used. The open circles show the charge ratio when the neutrino data is modified using heavy target shadowing corrections from charged lepton reactions, and the
solid circles show the results calculated specifically for neutrinos using our two phase model. For $x \geq 0.1$, the two shadowing corrections give essentially identical results. At small $x$, careful consideration of neutrino shadowing corrections decreases, but does not resolve, the low-$x$ discrepancy between the CCFR and NMC data.

At this point it is instructive to review how the structure functions are extracted in neutrino reactions. Because of the extremely small cross sections, it is necessary to integrate cross sections over all energies in order to accumulate sufficient flux. When this has been done, the resulting neutrino and antineutrino cross sections give two equations in the neutrino structure functions. If we assume that the neutrino and anti-neutrino structure functions are equal $F_2^\nu(x, Q^2) = F_2^\bar{\nu}(x, Q^2)$, with an analogous relation for $xF_3(x, Q^2)$, then we have two linear equations in two unknowns. From Eq. (2) we see that these relations will be true if charge symmetry is valid and if $s(x) = \bar{s}(x)$; there is an additional correction to $xF_3^\nu$ and $xF_3^\bar{\nu}$ from strange quarks.

The resulting structure function $F_2^{CCFR}$ is a flux weighted average between neutrino and anti-neutrino structure functions (see Ref. [1]). This fact becomes important if charge symmetry is violated or the strange and anti-strange quark distributions are different. If we define $\alpha = N_\nu/(N_\nu + N_\bar{\nu})$, where $N_\nu$ and $N_\bar{\nu}$ are the number of neutrino and anti-neutrino events, respectively, $F_2^{CCFR}(x, Q^2)$ is proportional to

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

$$= \frac{1}{2}[F_2^\nu(x, Q^2) + F_2^{\bar{\nu}}(x, Q^2)] + \frac{1}{2}(2\alpha - 1)[F_2^\nu(x, Q^2) - F_2^{\bar{\nu}}(x, Q^2)].$$

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 (which implies $s(x) = \bar{s}(x)$ and the validity of charge symmetry). The CCFR-Collaboration collected 1,300,000 neutrino and 270,000 anti-neutrino events; thus $\alpha \approx 0.83$ so that to a good approximation $F_2^{CCFR}(x, Q^2)$ 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 $s(x) \neq \bar{s}(x)$ [13], or from charge symmetry violation. First, we examine the role played by the strange and anti-strange quark distributions. Assuming charge symmetry, the strange and anti-strange quark distributions are given by a linear combination of the structure functions measured in neutrino and in muon DIS,

$$\frac{5}{6}F_2^{CCFR}(x, Q^2) - 3F_2^{NMC}(x, Q^2) = \frac{1}{2} x[s(x) + \bar{s}(x)] + \frac{5}{6}(2\alpha - 1) x[s(x) - \bar{s}(x)].$$

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 the distribution extracted from independent experiments.

The strange quark distribution can be determined directly from opposite sign dimuon production in deep inelastic neutrino and anti-neutrino scattering. The CCFR Collaboration performed a LO [14] and NLO analysis [15] of their dimuon data using the neutrino (antineutrino) events to extract the strange (anti-strange) quark distributions. They found that $s(x)$ and $\bar{s}(x)$ were equal within experimental errors in NLO [15]. However, since the number of anti-neutrino events is much smaller than that of the neutrino events, the errors of this analysis are inevitably large.
Since the dimuon experiments are carried out on an iron target, shadowing corrections could also modify the extracted strange quark distribution. The CCFR-Collaboration normalized the dimuon cross section to the “single muon” cross section and argued that the heavy target correction should cancel in the ratio. However, the charm producing part of the structure function \( F_2^{cp}(x, Q^2) \) could in principle be shadowed differently from the non-charm producing part \( F_2^{ncp}(x, Q^2) \). We tested this hypothesis by calculating the neutrino shadowing corrections for both the charm and non-charm producing part of the structure function. The results will be published separately \([16]\). We find that, while the relative importance of the Pomeron and VMD components are different in the charm producing \((cp)\) and the non-charm producing \((ncp)\) parts, there is essentially no difference in the total shadowing.

It appears plausible that the low-\(x\) discrepancy in the charge ratio of Eq. \(3\) can be accounted for by allowing \(s(x) \neq \bar{s}(x)\). To test this hypothesis we combined the dimuon production data, averaged over \(\nu\) and \(\bar{\nu}\) events, with the structure functions from neutrino and charged lepton scattering \(\text{(Eq.}(5)\)). Defining \(\alpha' = N_{\nu}/(N_{\nu} + N_{\bar{\nu}})\), where \(N_{\nu} = 5,030\), \(N_{\bar{\nu}} = 1,060\) \((\alpha' \approx 0.83)\) are respectively the \(\nu\) and \(\bar{\nu}\) events from the dimuon production experiment \([17]\), the flux-weighted experimental distribution \(xs(x)\) from dimuon production is

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

This equation together with Eq.\((5)\) forms 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 \(xs(x)\) \((\text{open circles})\) and \(\bar{x}s(x)\) \((\text{solid circles})\) by solving the resulting linear equations, Eqs. \(3\) and \(4\). The results are completely unphysical, since the extracted anti strange quark distribution is negative. Our analysis strongly suggests that requiring charge symmetry, but allowing \(s(x) \neq \bar{s}(x)\), cannot resolve the discrepancy between \(F_2^{CCFR}(x, Q^2)\) and \(F_2^{NMC}(x, Q^2)\). The experimental results are incompatible, even if \(\bar{s}(x)\) is completely unconstrained \([14]\).

As neither neutrino shadowing corrections nor allowing \(s(x) \neq \bar{s}(x)\) removes the low-\(x\) discrepancy between the neutrino and muon structure functions, there remain two possible explanations. Either one of the experimental structure functions \(\text{(or the strange quark distribution)}\) 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 the strange quark distribution \(\text{(Eq.}(3)\)}\) with the relation between neutrino and muon structure functions, Eq. \(3\) to obtain

\[
\frac{5}{6} F_2^{CCFR}(x, Q^2) - 3 F_2^{NMC}(x, Q^2) - xs^{\mu\mu}(x) = \frac{x(2\alpha - 1)}{3} [s(x) - \bar{s}(x)]
\]

\[
+ \frac{x}{6} [(5\alpha - 1)(\delta d(x) - \bar{\delta}d(x)) + (4 - 5\alpha)(\delta d(x) - \bar{\delta}u(x))]
\]

\[
\approx \frac{x(2\alpha - 1)}{3} [s(x) - \bar{s}(x)] + \frac{1}{2} x [\delta d(x) - \bar{\delta}u(x)].
\]

In Eq. \(3\) we have used the experimental value \(\alpha = \alpha'\). Since the experimental discrepancy is primarily in the small \(x\)-region, where sea quark distributions are much larger than valence quarks, CSV effects should appear predominantly in the sea quark distributions. Setting \(\delta q_{\nu}(x) = \delta q(x) - \bar{\delta}q(x) \approx 0\) in this region gives the second relation in Eq. \(3\).
The left hand side of Eq. 7 is positive. Consequently, the smallest CSV effects will be obtained by setting $\bar{s}(x) = 0$. In Fig. 3 we show the magnitude of charge symmetry violation needed to satisfy the experimental values in Eq. 7. The solid circles are obtained if we set $\bar{s}(x) = 0$, and the open circles result from setting $\bar{s}(x) = s(x)$. Both the structure functions and the dimuon data have been integrated over the overlapping kinematical regions. In averaging the dimuon data we used the CTEQ4L parametrization for $s^{\mu\mu}(x)$ [19], and we extracted the strange quark distributions according to Eq. 6. The CSV effect required to account for the NMC-CCFR discrepancy is extraordinarily large. It is roughly the same size as the strange quark distribution at small $x$. This CSV term is roughly 25% of the light sea quark distributions for $x < 0.1$. The existing experimental data thus appears to require a very surprising, and uncomfortably large, violation of parton charge symmetry at small $x$.

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 at least two orders of magnitude larger than theoretical estimates of charge symmetry violation [20,21]. We will discuss the implications of such a large violation of charge symmetry in a subsequent paper [16]. Theoretical considerations suggest that $\delta \bar{d}(x) \approx -\delta \bar{u}(x)$ [20]. We note that with this sign CSV effects also require large flavor symmetry violation. At small $x$, our results can be summarized by

$$
\delta \bar{d}(x) - \delta \bar{u}(x) \approx \frac{1}{4} \left( \frac{\bar{u}(x) + \bar{d}(x)}{2} \right) \approx \frac{1}{2} (s(x) + \bar{s}(x))
$$

$$
\delta \bar{d}(x) + \delta \bar{u}(x) \approx 0 \quad (x < 0.1)
$$

This suggests that for $x < 0.1$, $\bar{d}(x) \approx 1.25 \bar{u}(x)$ and $\bar{u}(x) \approx 0.75 \bar{d}(x)$. 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 re-analyze the extraction of all parton distributions.

This work is supported in part by the Australian Research Council, and by the National Science Foundation under research contract NSF-PHY9722706. One of the authors [JTL] wishes to thank the Special Research Centre for the Subatomic Structure of Matter for its hospitality during the period when this work was carried out.
REFERENCES

[1] G. A. Miller, B. M. K. Nefkens and I. Slaus, Phys. Rep. 194 (1990) 1; E. M. Henley and G. A. Miller in Mesons in Nuclei, eds M. Rho and D. H. Wilkinson (North-Holland, Amsterdam 1979).
[2] J.T. Londergan and A.W. Thomas, to be published in Progress in Particle and Nuclear Physics, 1998.
[3] NMC-Collaboration, P. Amaudruz et al., Phys. Rev. Lett. 66 (1991) 2712; Phys. Lett. B295 (1992) 159.
[4] K. Gottfried, Phys. Rev. Lett. 18 (1967) 1174.
[5] NA51-Collaboration, A. Baldit et al., Phys. Lett. B332 (1994) 244.
[6] E866-Collaboration, E. A. Hawker et al., to be published in Phys. Rev. Lett.
[7] B.-Q. Ma, Phys. Lett. B274 (1992) 433; B.-Q. Ma, A. W. Schäfer and W. Greiner, Phys. Rev. D47 (1993) 51.
[8] J. T. Londergan, S. M. Braendler and A. W. Thomas, Phys. Lett. B424, 185 (1998); J. T. Londergan, Alex Pang and A.W. Thomas, Phys. Rev D54 (1996) 3154.
[9] CCFR-Collaboration, W.G.Seligman et al., Phys. Rev. Lett. 79, 1213 (1997) and W.G.Seligman Ph.D. Thesis, Nevis Report 292.
[10] NMC-Collaboration, M.Arneodo et al., Nucl. Phys. B483, 3 (1997).
[11] C. Boros, J. T. Londergan and A. W. Thomas, (preprint hep-ph/9804411).
[12] J. Kwiecinski and B. Badelek, Phys. Lett. B208, 508 (1988); W. Melnitchouk and A.W. Thomas, Phys. Lett. B317, 437 (1993); Phys. Rev. C52, 3373 (1995).
[13] W. Melnitchouk and M. Malheiro, Phys. Rev. C55, 431 (1997); X. Ji and J. Tang, Phys. Lett. B362, 182 (1995); H. Holtmann, A. Szczurek and J. Speth, Nucl. Phys. A596, 631 (1996).
[14] S.A.Rabinowitz et al., CCFR-Collaboration, Phys. Rev. Lett. 70, 134 (1993).
[15] CCFR-Collaboration, A.O. Bazarko et al., Z. Phys. C65, 189 (1995).
[16] C. Boros, J.T. Londergan and A.W. Thomas, to be published.
[17] In Ref. [18] it was suggested that allowing $s(x) \neq \bar{s}(x)$ could account for the difference between the two determinations of the strange quark distribution. This result was obtained by assuming $\alpha = \frac{1}{2}$ in Eq. and $\alpha' = 1$ in Eq. The choice $\alpha = \frac{1}{2}$ does not agree with experiment ($\alpha = 0.83$).
[18] S.J.Brodsky and B.Q.Ma, Phys. Lett. B381, 317 (1996).
[19] H. L. Lai et al., Phys. Rev. D55, 1280 (1997)
[20] E. Rodionov, A. W. Thomas and J. T. Londergan, Mod. Phys. Lett. A9, 1799 (1994); C.J. Benesh and J.T. Londergan, preprint nucl-th/9803017.
[21] E. Sather, Phys. Lett. B 274, 433 (1992); C.J. Benesh and T. Goldman, Phys. Rev. C55, 441 (1997).
FIG. 1. The “charge ratio” as a function of $x$ calculated using the CCFR data for neutrino and NMC data for muon structure functions. The data have been integrated over the overlapping kinematical regions and have been corrected for heavy target effects using a parametrization (dotted line) for heavy target corrections extracted from charged lepton scattering (shadowing “(a)”). The result is shown as open circles. The ratio obtained without heavy target corrections and with shadowing corrections calculated in the “two phase” model (shadowing “(b)”) are shown as solid triangles and circles, respectively. The calculated heavy target correction factors for neutrino and for charged lepton scattering are represented by solid and dashed lines, respectively. Statistical and systematic errors are added in quadrature.
FIG. 2. The strange quark distribution $s(x)$ (open circles) and anti-strange distribution $\bar{s}(x)$ (solid circles) extracted by combining the CCFR and NMC structure functions with $s(x)$ extracted from dimuon experiments, as given in Eqs. 5 and 6. The difference between the CCFR neutrino and NMC muon structure functions $5/6 F_2^{CCFR} - 3 F_2^{NMC}$ is shown as solid triangles. The strange quark distribution extracted by the CCFR in a LO-analysis (Ref. [14]) is shown as solid stars, that from a NLO-analysis (Ref. [15]) is represented by the solid line with a band indicating $\pm 1\sigma$ uncertainty in the distribution. Statistical and systematic errors are added in quadrature.
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 $s(x) = \tilde{s}(x)$ (open circles) and $\tilde{s}(x) \approx 0$ (solid circles). Statistical and systematic errors are added in quadrature.