Testing Parton Charge Symmetry at HERA

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Abstract

There are strong theoretical indications that the minority valence quark distributions in the nucleon may break charge symmetry by as much as 3-5%. We show that a comparison of $e^\pm D$ deep inelastic scattering through the charged current, for example at HERA, could provide a direct test of this effect. This measurement is also be sensitive to an intrinsic component of the strange quark sea which leads to $s \neq \bar{s}$.

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The assumption of charge symmetry is an essential element of all current, phenomenological analyses of deep inelastic scattering data in terms of parton distributions. We recall that charge symmetry is the invariance of a Hamiltonian under a rotation by 180° about the 2-axis in isospace:

\[
[e^{i\pi I_2}, H_{CS}] = 0. \tag{1}
\]

It is a much more restrictive symmetry than isospin (i.e., charge independence), which requires \([I_i, H_{CS}] = 0, i = 1, 2, 3\). (Here \(I_i\) is the generator of the \(i\)'th component of rotations in isospace.) A charge symmetry transformation maps \(n\) into \(p\) and \(d\) into \(u\) (and vice versa), so charge symmetry at the quark level requires

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

\[
d^n(x) = \bar{u}^p(x) \quad ; \quad \bar{u}^n(x) = \bar{d}^p(x). \tag{2}
\]

Charge symmetry thus reduces the number of light quark distributions to be extracted from data by a factor of two [1]. All parton distributions for the neutron can be expressed in terms of those for the proton.

Studies of charge symmetry and charge independence in nuclear systems are very well developed [2]. While the latter is quite often broken at the 5% level, the former is usually reliable to 1% or better. Theoretical estimates of charge symmetry violation (CSV) in parton distributions were only made a few years ago. This was motivated by the successful calculations of charge symmetric parton distributions in the nucleon [6–9]. In these calculations, parton distributions were obtained from the relation

\[
q(x, \mu^2) = M \sum_X |\langle X | \psi_+ (0) | N \rangle|^2 \delta(M(1 - x) - p^+_X) . \tag{3}
\]

In Eq.(3), \(X\) represents a complete set of eigenstates for the residual system. The parton distribution \(q(x, \mu^2)\) is guaranteed to have proper support, i.e. it vanishes for \(x > 1\). One can easily see that the lowest-mass intermediate states dominate the sum over states in the valence region and extensive investigation has shown that simple models, like the MIT bag [10], are capable of explaining the shapes of the charge symmetric parton distributions.

Beginning with Sather [3] and Londergan et al. [4,5], it was realized that the dominant contribution to parton CSV should arise from mass differences in the eigenstates \(p^+_X\) in Eq.(3), rather than from the quark wavefunctions. In this case, expressions for the parton CSV terms could be obtained from the charge symmetric parton distributions. The dominant effect for valence quarks turned out to be the \(u - d\) mass difference for the spectators to the struck quark. As a consequence, the biggest percentage effect occurred in the “minority” distribution \(d^n(x) - u^n(x)\), where the \(u - d\) mass difference enters twice (the valence spectators being \((uu)\) and \((dd)\), respectively).

Suppose we define the valence CSV quantities \(\delta d_V\) and \(\delta u_V\) as:

\[
\delta d_V(x) = d_V^p(x) - u_V^p(x);
\]

\[
\delta u_V(x) = u_V^p(x) - d_V^p(x), \tag{4}
\]

then it was found that \(\delta d_V(x) \approx -\delta u_V(x)\) [5]. As the ratio \(d_V/u_V\) becomes small at large Bjorken \(x\) [11], the relative CSV effect is much bigger in \(\delta d_V(x)/d_V(x)\) than \(\delta u_V(x)/u_V(x)\).
For example, Rodionov et al. [4] found that the latter was never greater than 1%, as expected, whereas the former could be as large as 5-10% at intermediate values of $x$. Sather [3] suggested that $\delta d_V(x)/d_V(x)$ could grow to $3\%$ – a value supported by recent work by Benesh and Goldman [12] – c.f. however, Ref. [3].

In summary, it seems very likely that the minority valence distributions, $d_V^p(x)$ and $u_V^n(x)$, may break charge symmetry by $3\%-5\%$. Experimental confirmation of such an unexpectedly large effect would be extremely important. Until now the best proposal to determine $\delta d_V(x)$ and $\delta u_V(x)$ has involved $\pi^+D$ Drell-Yan [3]. That analysis is somewhat complicated by the possibility of CSV in the quark distributions of the pion, that is a non-zero value of $\bar{d}\pi^+ - u\pi^-$. In this paper, we discuss the possibility of extracting information on CSV by analyzing charged current deep-inelastic scattering from an isoscalar target. In particular, we examine the possibilities for comparing charged-current DIS from electrons or positrons on deuterium, which could be performed in the future at HERA.

At the enormous values of $Q^2$ that can be probed at HERA, charge current (CC) weak interaction processes such as $e^-p \to \nu_e X$ are not impossibly suppressed with respect to the electromagnetic process $e^-p \to e^-X$. In future experiments at HERA, one should have both $e^-$ and $e^+$ beams, and current plans call for colliding beams involving heavier nuclei, such as $D$, in a few years [13]. The $(e^-, \nu_e)$ reaction proceeds through absorption of a $W^-$ by the target partons. It couples only to the positively charged partons in the target, so that for a deuteron target the structure function (per nucleon) is [1]

$$F_1^{W^-D}(x) = \left[ u^p(x) + \bar{d}^p(x) + u^n(x) + \bar{d}^n(x) + 2s(x) + 2c(x) \right]/2. \quad (5)$$

(For simplicity we denote the $(e^-, \nu_e)$ reaction by the charge of the virtual $W$ absorbed by the target.) Eq.(5) is true under the following conditions. We assume that the measurements occur at energies and momentum transfers well above heavy quark production thresholds. We also neglect terms in the CKM quark mixing matrix of the order of $|V_{ub}|^2 \sim |V_{td}|^2 \sim 1 \times 10^{-4}$. If we have a positron beam, then the $(e^+, \bar{\nu}_e)$ deep-inelastic reaction measures only the negatively charged partons:

$$F_1^{W^+D}(x) = [d^p(x) + \bar{u}^p(x) + d^n(x) + \bar{u}^n(x) + 2s(x) + 2\bar{c}(x)]/2. \quad (6)$$

Taking the difference of the $e^+$ and $e^-$ CC cross sections one therefore has

$$\delta F_1(x) \equiv F_1^{W^+D}(x) - F_1^{W^-D}(x) = \frac{\delta d_V(x) - \delta u_V(x)}{2} + s(x) - \bar{s}(x) - c(x) + \bar{c}(x). \quad (7)$$

Eq.(7) demonstrates that any difference between these structure functions will arise from either parton CSV, or from differences between the $s$ and $\bar{s}$ distributions (or $c$ and $\bar{c}$ distributions) in the nucleon. Furthermore, the relation holds for all $x$ values. Since the charged current weak interaction process is rare, it would be essential to have very accurate calibration of the electron and positron flux. Detector efficiencies would not be a major problem, as the signal involves prominent jets on the hadron side and large missing energy and momentum on the lepton side.

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1We have also ignored any tiny corrections which might arise because $s^p \neq s^n$ or $c^p \neq c^n$. 

3
If, as is commonly assumed, \( s(x) = \tilde{s}(x) \) and \( c(x) = \tilde{c}(x) \), Eq.(7) provides a direct measure of the CSV in the parton distributions. On the other hand, there has been quite a lot of interest recently [13] - [18] in the possibility (first discussed in Ref. [19]) that \( s(x) - \tilde{s}(x) \) might be non-zero – with at least some suggestion of experimental support for the idea [20]. We show below the estimate of \( s - \tilde{s} \) calculated by Melnitchouk and Malheiro [15]. This is quite dependent on the form factor at the NKΛ vertex which is not well known. Clearly it will be important to determine first whether or not \( F_{1}^{W+D} - F_{1}^{W-D}(= \delta F_{1}) \) is experimentally non-zero. The interpretation in terms of CSV, \( s \neq \tilde{s} \) or possibly both, can then be pursued in detail.

In order to illustrate the size and shape of the effect expected we have evolved the values of \( \delta d_{V} \) and \( \delta u_{V} \) calculated in Ref. [4] – as shown at \( Q^{2} = 10 \text{ GeV}^{2} \) in Fig. 1(a) of Ref. [4] – to values of \( Q^{2} \) appropriate to HERA. The NLO QCD evolution of the distributions was carried out using the Mellin transformation technique. By the use of this technique one easily transforms the classical DGLAP equations [1,21] into a system of ordinary differential equations. This is principally done using Mellin moments,

\[
M^{N}(Q^{2}) = \int_{0}^{1} dx x^{N-1} F(x, Q^{2})
\]

(8)
to transform from \( x \)-space to complex \( N \)-space. In order to regain the evolved distribution, once the evolution equations have been evaluated, the results must be transformed back to \( x \)-space by the inverse Mellin transform. This is performed by a contour integral in the complex \( N \)-plane,

\[
F(x, Q^{2}) = \frac{1}{\pi} \int_{0}^{\infty} dz \, \text{Im} \left[ e^{i\phi} x^{-c-ze^{i\phi}} M^{n=c+ze^{i\phi}}(Q^{2}) \right],
\]

(9)
in which the contour of integration, and hence the value of \( c \), must lie to the right of all singularities of \( M^{N} \) in the complex \( N \) plane. For all the practical calculations, we have chosen to use the same values for \( z \) and \( \phi \) that were used in the original paper of Glück, Reya and Vogt [22]. The major advantage of using the Mellin transformation method for computing the evolution of the moments is that it does not involve the tremendous amount of computing time that previous methods employed. The resulting predictions for \( \delta u_{V} \) and \( \delta d_{V} \) at \( Q^{2} = 100, 400 \) and 10000 GeV\(^{2} \) are shown in Fig. 1.

In order to indicate the relative size of the difference in the \( e^{\pm}D \) cross sections expected, we divide the difference \( F_{1}^{W+D} - F_{1}^{W-D} \) by the average of \( F_{1}^{W+D} \) and \( F_{1}^{W-D} \) to obtain:

\[
R(x) = \frac{F_{1}^{W+D}(x) - F_{1}^{W-D}(x)}{F_{1}^{W+D}(x) + F_{1}^{W-D}(x)} = \frac{\delta d_{V}(x) - \delta u_{V}(x) + 2(s(x) - \tilde{s}(x))}{\sum_{j=p,n} [u^{j}(x) + \bar{u}^{j}(x) + d^{j}(x) + \bar{d}^{j}(x)] + 2(s(x) + \tilde{s}(x))} = R_{\text{CSV}}(x) + R_{s}(x).
\]

(10)

In Eq.(10), \( R_{\text{CSV}} \) is the charge-symmetry breaking term, and \( R_{s} \) is the term proportional to \( s - \tilde{s} \). In this equation we have neglected terms proportional to \( c \) and \( \tilde{c} \) since we expect them to be quite small, and in addition we know of no quantitatively reliable model for this quantity – see, however, Ref. [24] for an estimate of the intrinsic charm of the proton in the context of the HERA anomaly.
For the combination $F_1^{W+D} + F_1^{W-D}$ we evolved the CTEQ4Q parton distributions \cite{23} from their starting scale ($Q_0^2 = 1.6 \text{ GeV}^2$) to the same values of $Q^2$ used for $\delta d_V$ and $\delta u_V$. The results for $R_{CSV}$ are shown in Fig. 2, at several values of $Q^2$. We see that the CSV contribution to the cross section rises from 1% at $x = 0.4$ to 2% at $x = 0.6$. The prediction is not shown above $x = 0.8$ because the original bag model predictions were not reliable at very large $x$ and the cross section is, in any case, too small in that region.

In view of the appearance of $s - \bar{s}$ in Eq.\(\text{(7)}\), we have taken the recent work of Melnitchouk and Malheiro \cite{15} as an indication of the possible size of the effect. These authors evaluated the strange quark distributions in a “meson-cloud” picture, where the $\bar{s}$ sea arises from the kaon cloud of the nucleon, while the $s$-sea arises from the spectator strange baryon, namely $\Lambda$ or $\Sigma$. We have chosen to show their prediction \cite{25} with a (monopole) form factor of mass 1 GeV, which is the largest value consistent with the latest CCFR data \cite{20}. Figure 3 shows the corresponding ratio $R_s$ at the same values of $Q^2$ as shown in Figs. 1 and 2. Clearly the order of magnitude of the effect caused by $s - \bar{s}$ is very similar to that arising from CSV. Nevertheless, the shapes are completely different and one would expect to be able to separate the two phenomena on the basis of the measured $x$-dependence of $R$.

In conclusion, we note that although both the CSV and strangeness effects are predicted to be at the level of a few percent, the measurement of the difference in $e^\pm D$ cross sections at the momentum transfers typical of HERA is a very “clean” experiment. \textit{Any deviation from zero, at any value of $x$, would be extremely interesting}, whether its origin lies in CSV or intrinsic strangeness. Since there are both electron and positron beams at HERA and future plans for deuteron beams, we hope that this comparison can be made in the near future.

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FIG. 1. (a) The charge symmetry violation in the valence down quark distribution. (b) The charge symmetry violation in the valence up quark distribution.
FIG. 2. The charge symmetry violating ratio $R_{CSV}$ defined in Eq.(10).

FIG. 3. The relative contribution to the difference in $e^\pm$ cross sections arising from a possible difference $s - \bar{s}$ – labelled $R_s$ in Eq.(10).