HERA Anomaly and Hard Charm in the Nucleon

W. Melnitchouk\textsuperscript{1} and A. W. Thomas\textsuperscript{2}

\textsuperscript{1} Department of Physics, University of Maryland, College Park, Maryland 20742, USA
\textsuperscript{2} Department of Physics and Mathematical Physics, and Special Research Center for the Subatomic Structure of Matter, University of Adelaide, Adelaide 5005, Australia

Abstract

We explore the possibility that the excess neutral and charged current events seen by the H1 and ZEUS Collaborations at HERA at large $x$ and $Q^2$ could arise from a hard charm component of the nucleon. While the symmetric intrinsic charm hypothesis is unable to account for the HERA anomaly, a non-symmetric charm distribution generated non-perturbatively, for which $\bar{c}$ is much harder than $c$, can produce significant enhancement of cross sections at the HERA kinematics.

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The recent observation by the H1 [1] and ZEUS [2] Collaborations at HERA of an excess of events at large $x$ and $Q^2$ in $e^+p$ neutral current (NC) and charged current (CC) deep-inelastic scattering (DIS) has prompted numerous speculations about whether one has seen evidence for physics beyond the standard model. Most explanations have concentrated on leptoquarks or contact interactions as the source for the anomalously large cross sections — for a recent overview of the theoretical discussions see Ref. [3]. Using a simple, non-perturbative model for the intrinsic charm component of the nucleon wave function, we find a hitherto unnoticed asymmetry, with the $c$ component significantly harder than $\bar{c}$, which has important consequences for the HERA NC and CC events. Confirmation of such an asymmetry would challenge our understanding of the non-perturbative structure of hadrons within QCD.

The ZEUS experiment collected only NC data, while H1 observed both NC and CC DIS events. The evidence for the excess was found in data with $Q^2 > \sim 10000 \text{ GeV}^2$, and with an invariant mass $M = \sqrt{s x}$ of the virtual photon—parton system above $M \sim 150 \text{ GeV}$, where $x$ is the Bjorken variable, and $s \approx (300 \text{ GeV})^2$ is the $e^+p$ center of mass energy squared. For $Q^2 > 35000 \text{ GeV}^2$ two events were observed in the ZEUS data [2] while $~\sim 0.15$ were expected from the standard DIS model, and for $x > 0.55$ and $y = M^2/Q^2 > 0.25$ four events were found with $~0.9$ anticipated. For $Q^2 > 15000 \text{ GeV}^2$ the H1 data sample contained 12 NC (4 CC) events, where $~4.7 (1.8)$ were expected. On the face of it, this would amount to a probability of $\lesssim 1\%$ that the excess events arise from statistical fluctuations within the standard model. On the other hand, it has been argued [4] that the H1 and ZEUS data sets are at present as incompatible with each other as each is with the standard DIS model, so that more data analysis would be needed before definitive conclusions could be reached.

Given the importance of the potential discovery of new physics, if the excess persists in future HERA data it will be essential that one exhausts all possibilities that the phenomenon can be accommodated within standard model parameters. Recently, Kuhlmann, Lai and Tung [5] have suggested that an increased valence $u$ quark distribution at large $x$ could enhance the deep-inelastic cross sections appreciably. The suggested modification to the valence $u$ distribution, $u_V(x) \rightarrow u_V(x) + \delta u(x)$, where

$$\delta u(x) = 0.02 (1-x)^{0.1}, \quad (1)$$

is rather hard, as illustrated in Fig.1. Kuhlmann et al. [5] observed that through the QCD evolution feed-down effect, evolving this component from $Q^2 \sim 25 \text{ GeV}^2$ to $Q^2 \sim 40000 \text{ GeV}^2$ increases the standard model cross section significantly beyond $x = 0.75$, without sacrificing the quality of the global fits to existing data at lower energies.

While a distribution of type (1) can lead to better agreement with the HERA data, the physical origin of such a hard component of the $u$ quark distribution is difficult to motivate, given the small mass of the $u$ quark. In addition, it was argued in a recent reanalysis [6] of SLAC data for $x > 0.7$ that the proposed modification [5] would overestimate the large-$x$ data by some two orders of magnitude.

Another possibility raised in Ref. [5] is that the charm quark distribution might be enhanced at large $x$. Because the couplings of $u$ and $c$ quarks to electroweak bosons are identical, the effect of a modified $c$ distribution would be the same as that of a modified $u$. In addition, one could more easily imagine that the charm quark distribution could be rather hard, owing to the large $c$ quark mass. Such a component would of course have
to be generated non-perturbatively, since the charm quark distribution arising from gluon
bremsstrahlung alone looks like a typical soft sea distribution, namely peaks at \( x \to 0 \)
and is negligible beyond \( x \sim 0.4 \), Fig.1.

The effect of a non-perturbative, or intrinsic, charm component on the DIS cross sections
at HERA kinematics was recently investigated by Gunion and Vogt \[7\] within a model of the
5-quark component of the nucleon wave function on the light-cone \[8\]. Following Brodsky
et al. \[8\], the wave function was assumed to be inversely proportional to the light-cone energy
difference between the nucleon ground state and the 5-quark excited state. The resulting
\( x \)-dependence of the inclusive \( c \) quark distribution in the minimal model of \[7\] was given by
\[8\]:

\[
\delta^{\text{IC}}(x) = 6x^2 \left((1 - x)(1 + 10x + x^2) - 6x(1 + x)\log 1/x\right),
\]

with normalization fixed to 1\% \[7\]. As seen in Fig.1, such a distribution peaks at \( x \sim 0.2 \),
and is negligible beyond \( x \sim 0.7 \). The anti-charm distribution is assumed to be equivalent
to the charm distribution in this model, \( \delta^{\text{IC}}(x) = \delta^{\text{IC}}(c)(x) \). After evolving to the HERA
kinematics, this intrinsic charm distribution, while considerably harder than that generated
through pQCD alone, is still too soft to account for the excess HERA events \[7\].

What one needs, therefore, is a substantially harder distribution which has significantly
more strength above \( x \sim 0.6 \) than in (2). In this paper we investigate whether one can
indeed obtain a sizable enhancement of the number of events at large \( x \) and \( Q^2 \) from a hard
charm distribution, and whether such a distribution can be motivated from any physical
model.

As an alternative to the intrinsic charm picture of Refs. \[7,8\], the charmed sea was taken
in Refs. \[9,10\] to arise from the quantum fluctuation of the nucleon to a virtual \( D^- + \Lambda_c \)
configuration. The nucleon charm radius \[8\] and the charm quark distribution \[10\] were both
estimated in this framework. The meson cloud model for the long-range structure of the
nucleon has been developed in Refs. \[11–13\] to describe various flavor symmetry breaking
phenomena observed in DIS and related experiments. It offers a natural explanation of
the \( d \) excess in the proton over \( u \) \[14\] in terms of a pion cloud, which itself is a necessary
ingredient of the nucleon by chiral symmetry. It also provides an intuitive framework to
study the strangeness content of the nucleon, through the presence of the kaon cloud of
the nucleon \[12,13\]. Whether the same philosophy can be justified for a cloud of heavy
charmed mesons and baryons around the nucleon is rather more questionable given the
large mass of the fluctuation. Nevertheless, to a crude approximation, we may take the
meson cloud framework as an indicator of the possible order of magnitude and shape of
the non-perturbative charm distribution. Furthermore, a natural prediction of this model is
non-symmetric \( c \) and \( \bar{c} \) distributions.

In the meson cloud model, the distribution of charm quarks in the nucleon on the light
cone at some low hadronic scale is written in convolution form:

\[
\delta\bar{c}(x) = \int_x^1 \frac{dz}{z} f_{D/N}(z) \bar{c}D^- \left(\frac{x}{z}\right), \quad \delta c(x) = \int_x^1 \frac{dz}{z} f_{\Lambda_c/N}(z) c\Lambda_c \left(\frac{x}{z}\right),
\]

where \( z \) is the fraction of the nucleon’s light-cone momentum carried by the \( D^- \) meson or
\( \Lambda_c \). The light cone (or infinite momentum frame) distribution of \( D^- \) mesons in the nucleon
is given by:
\[ f_{D/N}(z) = \frac{1}{16\pi^2} \int_0^\infty dk_\perp^2 \frac{g^2(k_\perp^2, z)}{z(1-z)(s_{D\Lambda_c} - M_N^2)^2} \left( \frac{k_\perp^2 + [M_{\Lambda_c} - (1-z)M_N]^2}{1-z} \right), \tag{4} \]

and can be shown to be related to the light-cone distribution of \( \Lambda_c \) baryons, \( f_{\Lambda_c/N}(z) \), by \( f_{\Lambda_c/N}(z) = f_{D/N}(1-z) \).

In Eq.(4) the function \( g \) describes the extended nature of the \( D\Lambda_cN \) vertex, with the momentum dependence parameterized by \( g^2(k_\perp^2, z) = g_0^2(\Lambda^2 + M_N^2)/(\Lambda^2 + s_{D\Lambda_c}) \), where the \( D\Lambda_c \) center of mass energy squared is given by \( s_{D\Lambda_c} = (k_\perp^2 + M_B^2)/z + (k_\perp^2 + M_N^2)/(1-z) \), and \( g_0 \) is the \( D\Lambda_cN \) coupling constant at the pole, \( s_{D\Lambda_c} = M_N^2 \). We expect \( g_0 \) to be similar to the \( \pi NN \) coupling constant.

Because of the large mass of the \( c \) quark, one can approximate the \( \bar{c} \) distribution in the \( D^- \) meson \([10]\) and the \( c \) distribution in the \( \Lambda_c^+ \) by:

\[ \bar{c}^{D^-}(x) \approx \delta(x-1), \quad c^{\Lambda_c^+}(x) \approx \delta(x-2/3), \quad (5) \]

which then gives:

\[ \delta\bar{c}(x) \approx f_{D/N}(x), \quad \delta c(x) \approx \frac{3}{2} f_{\Lambda_c/N}(3x/2). \tag{6} \]

The resulting \( \delta c \) and \( \delta \bar{c} \) distributions are shown in Fig.1, calculated for an ultraviolet cutoff of \( \Lambda \approx 2.2 \) GeV, which gives \( \int_0^1 dx \delta c(x) = \int_0^1 dx \delta \bar{c}(x) \approx 1\% \). For a probability of 0.5\% one would need a smaller cutoff, \( \Lambda \approx 1.7 \) GeV. Quite interestingly, the shape of the \( c \) quark distributions is quite similar to that in the intrinsic charm model of Refs. \([7,8]\). However, as mentioned above, the model of \([2,8]\) assumes identical shapes for the non-perturbative \( c \) and \( \bar{c} \) distributions, while the meson cloud gives a significantly harder \( \bar{c} \) distribution.

Calculation of the NC and CC cross sections requires parton distributions for all flavors. For this we use a recent parameterization of global data from the CTEQ Collaboration \([16]\). Expressions for the differential NC and CC cross sections \( d^2\sigma/dxdQ^2 \) in the standard model can be found in Refs. \([2,7]\) and \([17]\). In Fig.2 we show the ratios of the modified to standard DIS model NC cross sections, with \( \sigma \equiv d^2\sigma/dxdQ^2 \), and \( \sigma + \delta\sigma \) represents the cross section calculated with the modified distributions. The result with the modified \( u \) distribution \([3]\) rises sharply above \( M \sim 200 \) GeV. The effect is rather similar if one includes the non-perturbative \( \delta c \) and \( \delta \bar{c} \) distributions from the meson cloud model. On the other hand, with the somewhat softer, intrinsic charm distribution of \([2,8]\), the enhancement is rather modest, and \( \lesssim 10\% \) over the whole range of \( M \).

Also shown in Fig.2 is the effect of additional contributions to the light flavor distributions \( (u, \bar{u}, d, \bar{d}) \) which one would obtain from a pion cloud of the nucleon \([11]\). Although these are considerably larger in magnitude than the \( \delta c \) or \( \delta \bar{c} \) distributions, because they appear at small \( x \sim 0.1 \) their effect is to yield only a very small enhancement of the cross section ratio. From this figure one can conclude that the only realistic candidates for a significant enhancement of the cross section at large \( M \) are the modified valence \( u \) distribution from Ref. \([3]\), and the hard charm distributions in Eq.(6).

To compare with the H1 and ZEUS data one needs to evolve the cross sections to the typical scales relevant for HERA. Since the excess of events is seen at quite large \( Q^2 \), 10000 \( \lesssim Q^2 \lesssim 40000 \) GeV\(^2 \), we evolve the \( \delta u \) and \( \delta c \& \delta \bar{c} \) distributions to an average value of \( Q^2 \approx 20000 \) GeV\(^2 \). The result is shown in Fig.3, where for \( M \gtrsim 250 \) GeV especially one
has an enormous enhancement of the NC cross section. The enhancement is qualitatively similar for both the 0.5% and 1% $\delta \bar{c}$ components.

For scattering via the CC, the effect of the additional contributions to the parton distributions is shown in Fig.4 for $Q^2 = 20000 \text{ GeV}^2$. Since the $W^+\bar{b}$ boson is not sensitive to the $u$ quark in the proton, the $\delta u$ modification has no effect on the $e^+p$ cross section. In contrast, as noted by Babu et al. [18], the effect of an additional non-perturbative $\delta \bar{c}$ contribution is an even larger enhancement of the CC cross section than the NC cross section. With a 0.5% (1%) intrinsic charm component the CC cross section increases by a factor $\sim 2$ ($3$) for $200 \lesssim M \lesssim 250 \text{ GeV}$, which is similar to the excess observed by H1 [1] in this region.

Having seen that one can indeed modify the existing parton distributions at large $x$ to produce large enhancements of the cross sections at large $M$ and $Q^2$, the key question to address next is whether such modified distributions are compatible with existing data at lower $Q^2$. A recent analysis [4] of SLAC data at $0.7 \leq x \leq 0.97$ in and near the resonance region suggests that the proposed modification of the $u$ quark distribution in Ref. [1] would overestimate the large-$x$ data by two orders of magnitude. (Though one should keep in mind that the authors of Ref. [1] assume the validity of Bloom-Gilman duality even at very large $x$ values close to 1.) On the other hand, the values of $W^2$ corresponding to the $x$ and $Q^2$ bins are too low for the SLAC data to be sensitive to the charm component of the nucleon wave function. Data are, however, available from the BCDMS Collaboration in the region $x > 0.6$ which are above charm threshold [19]. The effect of adding the intrinsic $\delta \bar{c}$ distribution calculated from Eq.(6) to the data on the deuteron structure function (as parameterized in Ref. [20]) is illustrated in Fig.5. With the addition of the 0.5% contribution there does not seem to be any inconsistency with the data [19] and, indeed, the agreement is slightly improved at $x = 0.75$. On the other hand, the 1% case may be a little too high for comfort. Earlier data from the EMC [21] on the charm structure function extracted from charmed particle production in $\mu$–nucleus scattering also exist, but cover only the region below $x \sim 0.3$.

One can conclude, therefore, that a non-perturbatively generated hard charm distribution can significantly enhance the DIS cross sections at the large $x$ and $Q^2$ values attainable at HERA, and still be compatible with data at lower $Q^2$. We should make clear, however, that the $\delta c$ and $\delta \bar{c}$ quark distributions calculated in the meson cloud model should not be viewed as quantitative predictions, but rather as a physical motivation for a hard non-perturbative charm component of the nucleon. In particular, one can vary model parameters to modify the detailed shape of the distributions. For example, using a smaller power of $1/(\Lambda^2 + s_{DAc})$ in the hadronic vertex function $g(k^2, z)$ would result in a $\delta \bar{c}$ distribution with even more strength at $x > 0.75$ than that in Fig.1, which would further enhance the cross sections for $M \sim 200 - 250 \text{ GeV}$. Nevertheless, the fact that the model predicts a large asymmetry between $c$ and $\bar{c}$ distributions is a robust, and to our knowledge unique, feature of the meson cloud model.

Another possibility which could lead to additional enhancement of the cross sections at large $x$ would be a non-perturbative $\bar{b}$ quark component [3], although the magnitude of this would presumably be rather small compared with the $\bar{c}$. In addition, the recent reanalysis of the SLAC deuteron data in Ref. [22] suggested that the valence $d/u$ ratio does not tend to zero as $x \to 1$, as assumed in global fits to data [16], but rather is consistent with the expectation of perturbative QCD, namely $d/u \to 1/5$ [23]. Figure 6 shows the ratio of the
modified $d$ quark distribution, $d + \delta d$, extracted from the deuteron and proton data in Ref. [22] at $Q^2 \approx 10 \text{ GeV}^2$ and evolved to $Q^2 = 10000 \text{ GeV}^2$, to that used in the standard fits. The correction $\delta d$ is taken from the parameterization in Ref. [24]. The effect of the modified $d$ quark is not large in NC events, primarily due to the factor 4 charge suppression compared with $u$, but can be sizable for CC events, comparable to that of the 0.5% $\delta c$ scenario — as shown by the dashed curve in Fig.4. The fact that all standard sets of parton distributions assume that $d/u \to 0$ as $x \to 1$ means that there is a possible source of systematic error in the modeling of “background” events which should be accounted for.

The task of disentangling the origin of the HERA anomaly in future can be approached from several directions. Tagging charm final states in $J/\psi$ production could provide information on whether the large $x$ enhancement is due to charm or other flavors. A thorough comparison of NC and CC cross sections, for both $e^+p$ and $e^-p$ collisions, would also enable one to determine the flavor combinations responsible for the cross section enhancement [18]. One can also construct new distributions, such as those suggested in Ref. [25], which are insensitive to parton distributions, but sensitive to modifications of parton level cross sections, and which could therefore distinguish between explanations of the anomaly in terms of modifications of parton distributions and those invoking new physics.

 Needless to say, we eagerly await further results from the H1 and ZEUS Collaborations. Quite apart from the excitement over the possible discovery of physics beyond the standard model, the issue of whether or not the nucleon contains a significant component of intrinsic charm is extremely important. In particular, any experimental evidence supporting the suggestion that the intrinsic charm could have a strong asymmetry would mean a revision of current wisdom, and would undoubtedly lead us to a deeper understanding of the structure of hadronic systems. Whether H1 and ZEUS provide evidence for new physics beyond the standard model or map out hitherto unknown features of the non-perturbative structure of the nucleon, the results will be of great interest.

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FIG. 1. Modification $\delta u$ of the valence $u$ distribution from Ref. [5], compared with the light-cone intrinsic charm distribution, $\delta^{(IC)} c$, of Refs. [7,8], and the non-perturbative $\delta c$ and $\delta c_d$ distributions in the meson cloud model (the latter normalized to 1%). Also shown is the purely perturbative contribution at $Q^2 = 4 \text{ GeV}^2$.

FIG. 2. Ratio of modified to standard DIS model NC cross sections at the charm threshold, with the modifications arising from the additional $u$ quark component [5] (dashed), 1% non-perturbative $\delta c$ and $\delta c_d$ distributions from the meson cloud model (solid), and the intrinsic charm model of Refs. [7,8] (dot-dashed). Also shown is the effect of the meson cloud contributions to the light sea quarks [11] (dotted).
FIG. 3. Ratio of modified to standard DIS model NC cross sections at $Q^2 = 20000$ GeV$^2$. The modifications are from the extra $\delta u$ component, and from additional hard non-perturbative $\delta c$ and $\delta \bar{c}$ components, with 0.5% and 1% normalization.

FIG. 4. Ratio of modified to standard DIS model CC cross sections at $Q^2 = 20000$ GeV$^2$, with the modifications arising from 0.5% and 1% additional $\delta \bar{c}$ distributions, as well as a modified $d$ quark distribution at large $x$ (see Fig.6).
FIG. 5. Structure function of the deuteron, $F_{2D}$, with 0.5% (solid) and 1% (dashed) additions of non-perturbative charm to the global fit (dotted) from Ref. [20].

FIG. 6. Ratio of the modified $d$ quark distribution, $d + \delta d$, extracted from deuteron data in Ref. [22] at $Q^2 \approx 10$ GeV$^2$ and evolved to $Q^2 = 10000$ GeV$^2$, to that used in standard, global fits [16], which assume $d/u \to 0$ as $x \to 1$. 
