Intrinsic Charm at High-$Q^2$ and HERA Data

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Abstract

We compute the predictions of intrinsic charm for deep-inelastic scattering at high-$Q^2$ and compare to HERA data. With the inclusion of constraints from low-energy data, enhancements beyond the predictions of standard structure functions are very modest, but peaking in the leptoquark mass variable is present near 200 GeV. Ultimately, the ability of HERA to probe the intrinsic charm hypothesis could be very substantial.

HERA deep-inelastic scattering data with significant statistics at high $Q^2$ and high $x$ is now becoming available [1, 2]. The cross section exhibits an excess beyond the predictions based on standard QCD distribution functions. However, it is possible that unexpected contributions to the quark distribution functions might explain at least part of this excess [3]. In this Letter, we pursue the implications for the HERA data of an intrinsic charm (IC) component of the proton [4]. We find that intrinsic charm naturally predicts a peak in the leptoquark mass distribution in the vicinity of 200 GeV, but that existing constraints on intrinsic charm limit the size of the effect. As a function of leptoquark mass, the enhancement from intrinsic charm relative to standard model (SM) predictions is at most of order 15% in the $e^+p$ neutral current (NC) case but can be as large as 75% in $e^+p$ charged current (CC) scattering. Expectations for $e^-p$ NC and CC scattering are also given.

The possibility of an intrinsic charm component in the proton bound state has substantial theoretical and phenomenological motivation. However, a conclusive observation or severe limit has remained elusive. In the intrinsic charm model, there is a $|uudc\bar{c}\rangle$ component of the proton in which the $c$ and $\bar{c}$ have become completely integrated members of the bound state, travelling coherently with the light quarks. In the minimal model, the $|uudc\bar{c}\rangle$ wave function is taken to be proportional to the inverse of the light-cone energy difference $m_p^2 - \sum(x_i^2/x_i) \propto x_c x_{\bar{c}}/(x_c + x_{\bar{c}})$ where the $x_i$ are the light-cone momentum fractions and the light quark and proton masses are neglected compared to the charm quark mass. After squaring, the intrinsic charm Fock state probability distribution takes the form

$$\frac{dP_{ic}}{dx_u dx_u' dx_d dx_c dx_{\bar{c}}} = N_5 \frac{x_c^n x_{\bar{c}}^n}{(x_c + x_{\bar{c}})^n} \delta(1 - \sum_i x_i),$$

(1)
with $n = 2$. However, more extreme dependence on the light-cone energy difference is entirely possible and, indeed, very natural, given that the strong interactions will tend to bind the intrinsic charm quarks to the light quarks so that all move with essentially the same velocity. To exemplify this situation, we will also consider $n = 8$ in Eq. (1).

The inclusive charm quark distribution, $c(x)$, is obtained by integrating Eq. (1) over all the $x_i$ except $x \equiv x_c$. For $n = 2$ and $n = 8$, one finds

$$c(x) = \frac{1}{2} N_5 x^2 \left[ \frac{1}{3} (1 - x)(1 + 10x + x^2) + 2x(1 + x) \ln x \right] \quad (n = 2),$$

$$c(x) = \frac{1}{210} N_5 x^8 \left[ 35 + 1155x - 1575x^2 - 11375x^3 - 2450x^4 + 490x^5 - 96x^6 + 14x^7 - x^8 
+ x \left( 1443 + 7161x + 5201x^2 + \left\{ 840 + 5880x + 5880x^2 \right\} \ln x \right) \right] \quad (n = 8)$$

respectively. We adopt a normalization $N_5$ such that the intrinsic charm Fock state component of the proton has 1% probability, implying $N_5 = 36$ ($N_5 = 2888028$) for $n = 2$ ($n = 8$). The anti-charm distribution, $\bar{c}(x)$, is identical to $c(x)$. Thus, at leading order, the net contribution from intrinsic $c$ and $\bar{c}$ to the deep-inelastic electromagnetic structure function is $F_2^c \gamma^* (x) = 8x c(x) / 9$. Next-to-leading order QCD evolution corrections to the IC contribution to $F_2^c \gamma^* (x)$ are computed following the formalism outlined in Ref. [3]. (See also Ref. [4].) They are significant but evolve very slowly with $Q^2$.

In Fig. 1, we illustrate results for the electromagnetic structure function, $F_2^c \gamma^* (x)$ at $Q^2 = 25000 \text{GeV}^2$. First, we give the standard next-to-leading order prediction for $F_2^c \gamma^* (x)$ obtained by employing the recent MRS96(R2) distribution functions computed via perturbative QCD evolution, without inclusion of the IC component. Also shown is the $n = 2$ IC component alone and the SM plus $n = 2$ IC sum. A very modest enhancement in the vicinity of $x \sim 0.2$ is observed. Results for the $n = 8$ model for the intrinsic charm component and corresponding total $F_2^c \gamma^* (x)$ are also shown. A much more substantial enhancement is observed, peaking in the vicinity of $x \sim 0.3$.

The low-energy direct EMC measurement[8] of $F_2(x)$ provides some evidence for intrinsic charm. In Fig. 2, the EMC data for $v = 168 \text{GeV}$ is compared to several predictions for $F_2(x)$[4]. The first is the perturbative “extrinsic” charm prediction of Ref. [3]. In this approach, charm production in deep-inelastic scattering is computed to next-to-leading order using all relevant partonic-level subprocesses contributing to $\gamma^* p \to cX$. (In our comparison to this data, we employ the $\Lambda_{\overline{\text{MS}}} = 0.239 \text{GeV}$ CTEQ3 distribution set and use scale $\mu_0^2 = Q^2 + M_Z^2$ in all distribution function and evolution evaluations [3].) The most important aspect of the subprocess approach is that charm-quark mass effects near threshold are correctly incorporated. This is not true of the perturbative charm distributions contained in the CTEQ3 distribution.

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1In our QCD evolution computations for the intrinsic charm component, we employ $\Lambda_{\overline{\text{MS}}} = 0.344 \text{GeV}$, as appropriate for MRS96(R2), and $m_c = 1.5 \text{GeV}$. We use scale $Q$ in evaluating distribution functions and QCD-evolution corrections to $F_2^c \gamma^* (x)$.

2At the $Q^2$ values probed by EMC, the $Z^*$ contribution to $F_2$ is negligible compared to the $\gamma^*$ contribution.
set itself; these are obtained by effectively assuming that the charm quarks are massless. That correct inclusion of mass effects is critical in the EMC energy range is shown by the curve in Fig. 2 corresponding to the CTEQ3 charm distribution function. The other curves in Fig. 2 illustrate the result of adding intrinsic charm components with \( n = 2 \) and \( n = 8 \) to the extrinsic charm prediction. In agreement with Ref. [5], the \( n = 2 \) addition to the extrinsic charm distribution fits the data quite nicely. The \( n = 8 \) model provides equally good agreement with the data. Even larger values of \( n \) would still be consistent with the EMC data, but substantially larger probability for the IC wave function component would not.

ISR data on \( pp \to \Lambda_c + X \) [10] provides additional evidence for and constraints upon intrinsic charm [11, 12]. The production of \( \Lambda_c \) baryons can be viewed as arising from three sources. First, there is \( gg + q \bar{q} \) fusion production of a \( c \bar{c} \) pair, followed by \( c \to \Lambda_c \). Second, in inelastic \( pp \) collisions the \( c \) quark in the IC proton wave function component can fragment to a \( \Lambda_c \). Finally, also in inelastic collisions, the \( c \) quark in the IC component of the proton wave function can coalesce with a \( u \) and \( d \) quark to produce a \( \Lambda_c \); the \( x_F \) distribution of the \( \Lambda_c \) produced in this manner is obtained by integrating over all the parton momentum fractions in Eq. (1) with the constraint \( x_F = x_u + x_d + x_c \). Following the procedures of Refs. [11, 12], it is found that the shape of \( dN/dx_F \) at large \( x_F \geq 0.5 \) is dominated by the third, \( i.e. \) coalescence, term. This is illustrated in Fig. 3, where \( dN/dx_F \) is plotted for (i) fusion, (ii) fusion plus \( n = 2 \) IC and (iii) fusion plus \( n = 8 \) IC. In each case, the prediction is normalized to \( \sigma(x_F \geq 0.5) \).

We observe that the \( dN/dx_F \) data requires the presence of an intrinsic charm contribution, and that the \( n = 2 \) shape is preferred over the \( n = 8 \) shape. It is for this reason that we have chosen not to consider still higher \( n \) values in Eq. (1) for the IC model, despite the fact that higher \( n \) values would yield larger effects at HERA.

In order to compare to HERA data, we have chosen to compute the ratio of intrinsic charm plus the standard model perturbative prediction from MRS96(R2) to the MRS96(R2) prediction alone (a) as a function of \( Q^2 \) after integrating over \( 0.1 \leq y \leq 0.9 \) and (b) as a function of \( M \) after integrating over \( y \geq 0.4 \), where \( M = \sqrt{s} \) is the eq leptoquark mass. Experimental results for these ratios have been presented by H1 [1], and closely related results have been presented by Zeus [2]. These ratios appear in Figs. 4 and 5, respectively. Results for the \( n = 2 \) and \( n = 8 \) models are presented for \( e^+p \) and \( e^-p \), NC and CC reactions.

The \( Q^2 \) dependence in Fig. 4 shows that the \( n = 2 \) and \( n = 8 \) IC models predict \( e^+p \) NC enhancements that grow to roughly 6% and 12%, respectively, at high \( Q^2 \). Much larger enhancements are indicated in the present HERA data. If these large enhancements persist, they would have to have a primary source other than intrinsic charm. Further, the relatively small intrinsic charm component could probably never be isolated from the dominant source without charm tagging. In the alternative scenario, where the enhancements decline with

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3 In the \( n = 2 \) IC case, the best two-component EC+IC fit is obtained for \((1.27 \pm 0.06)F^E_{2C} + (0.92 \pm 0.53)F^C_{2C}\). The EC coefficient, 1.27, is not inconsistent with the expected \( K \) factor from higher order corrections, while the IC coefficient is consistent with a 1% IC probability. For the \( n = 8 \) curves, we have employed the same coefficients.

4 It is assumed that there is no extrinsic or perturbative \( c \) quark component to the proton wave function at the low momentum transfers involved.

5 Comparisons based on absolute normalizations are less reliable.
increased statistics, it is clear that the sensitivity to intrinsic charm could ultimately become very substantial.

Data from other reactions potentially provide further opportunity for probing intrinsic charm. The additional possibilities include $e^{-}p$ NC scattering and $e^{\pm}p$ CC scattering. The intrinsic charm contribution to both NC and CC reactions is the same for $e^{+}p$ and $e^{-}p$ scattering. The relative IC enhancement in $e^{-}p$ NC scattering is then much smaller than in $e^{+}p$ NC scattering due to the increased size of the SM cross section (deriving from the change in sign of the $F_{3}$ contribution). In contrast, relative enhancements in $e^{+}p$ CC deep-inelastic scattering will be much larger, exceeding 60% and 150% at $Q^{2} > 30000 \text{ GeV}^{2}$ for the $n = 2$ and $n = 8$ IC models, respectively. These larger enhancements occur because the SM $e^{+}p$ CC cross section is mainly proportional to the down quark distribution and is, therefore, suppressed compared to the SM $e^{+}p$ NC cross section, which is largely proportional to the much larger (at large $x$) up quark distribution. Very small enhancements are predicted in $e^{-}p$ CC scattering. (That the above systematics should apply has been pointed out in Ref. [13].)

The $(\text{SM+IC})/\text{SM}$ ratios as a function of the leptoquark mass, $M$, are particularly revealing. As seen in Fig. 5, the peak at moderate $x$ values in the intrinsic charm distribution function (see Fig. 1) results in a substantial peak in the $(\text{SM+IC})/\text{SM}$ ratio for $e^{+}p$ NC scattering in the vicinity of $M \sim 200 \text{ GeV}$, i.e. the same general location as the peak observed for data/SM by H1. Of course, the IC prediction for the height of the peak [$(\text{SM+IC})/\text{SM} = 1.06$ and 1.12 for the $n = 2$ and $n = 8$ IC models, respectively] is much smaller than that observed; data/SM $\sim 8$ at $M \sim 200 \text{ GeV}$ in the H1 data. Increased statistics will decisively determine whether or not the observed peak at $M \sim 200 \text{ GeV}$ in data/SM has anything to do with intrinsic charm. Observations of other reactions could prove very valuable. For example, the peaking in $(\text{SM+IC})/\text{SM}$ as a function of $M$ predicted by the IC models will be larger in $e^{+}p$ CC scattering than in $e^{+}p$ NC scattering; in the former case, the $(\text{SM+IC})/\text{SM}$ ratio reaches a maximum of 1.3 (1.7) in the $n = 2$ ($n = 8$) IC models for $M \sim 200 \text{ GeV}$.

As a final point of comparison, we have also evaluated the effect of adding an extra component, $\delta u(x) = 0.02(1 - x)^{0.1}$, to the valence $u$ quark distribution function, as considered in Ref. [3]. Results for such an addition (after evolution) are also shown in Figs. 4 and 5. We observe that, in the absence of other new physics contributions, data/SM as a function of $M$ will allow one to easily discriminate between this possibility and intrinsic charm.

In conclusion, we find that intrinsic charm is unable to explain enhancements in the $e^{+}p$ neutral current cross section as large as those seen at HERA, although a small peak in the vicinity of leptoquark mass $M \sim 200 \text{ GeV}$ is a natural prediction. In the absence of other new physics, HERA data will ultimately provide a sharp test of the intrinsic charm picture, especially once the charm component of $F_{2}$ is directly isolated.
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Figure 1: Predictions for $F_2^c \gamma^*(x)$ at $Q^2 = 25000 \text{GeV}^2$: solid — SM next-to-leading order prediction using MRS96(R2) distribution functions only; dots — the $n = 2$ IC component alone; dot-dashed — SM plus $n = 2$ IC; dashes — $n = 8$ IC only; dash-long-dash — SM plus $n = 8$ IC.
Figure 2: EMC data for $F_2^c(x)$ at $\overline{\nu} = 168$ GeV compared to: (i) dotdash — the extrinsic charm prediction of Ref. [5]; (ii) dots — the CTEQ3 perturbative prediction; (iii) solid — EC+IC prediction for $n = 2$; (iv) dashes — EC+IC prediction for $n = 8$. 
Figure 3: The $x_F$ distribution for $pp \rightarrow \Lambda_c + X$. Data from Ref. [10] is compared to: (i) dotdash — $gg + q\bar{q} \rightarrow c\bar{c}$ fusion followed by $c \rightarrow \Lambda_c$; (ii) solid — fusion plus $n = 2$ intrinsic charm contributions; (iii) dashes — fusion plus $n = 8$ IC contributions. A 1% probability for the IC component of the proton wave function is used to fix the IC cross section. In all three cases, the overall normalization is fixed by $\sigma(x_F \geq 0.5)$. 
Figure 4: Predictions of various models for \( \frac{d\sigma}{dQ^2} / d\sigma_{SM}/dQ^2 \) at HERA center-of-mass energy after integrating over \( 0.1 \leq y \leq 0.9 \). Results are shown for \( e^\pm p \) scattering and both neutral current (NC) and charged current (CC) scattering. Curve legend: solid — \( e^+ p \) scattering and \( n = 2 \) IC; dotdash — \( e^+ p, n = 8 \) IC; dashes — \( e^- p, n = 2 \) IC; dots \( e^- p, n = 8 \) IC; dash-dash-dot — \( e^+ p, \delta u(x) = 0.02(1 - x)^{0.1} \); dash-dot-dot — \( e^- p, \delta u(x) = 0.02(1 - x)^{0.1} \).
Figure 5: Predictions for $[d\sigma/dM]/[d\sigma^{SM}/dM]$ at HERA center-of-mass energy after integrating over $y \geq 0.4$. Notation as for Fig. 4; the dash-dash-dot curve in the NC window is not shown since it is nearly identical to the dash-dot-dot curve.