REAL PHOTOABSORPTION AND THE PROTON STRUCTURE FUNCTION AT LOW x

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ABSTRACT

We investigate real photoabsorption and proton structure function data from the laboratory frame viewpoint, in which the x dependence reflects the space-time structure of the process. Both the real and virtual photon data are well described by a simple model in which the striking enhancement observed at HERA at very low x and high Q^2 is associated with contributions from heavy long-lived fluctuations of the incoming photon. As Q^2 becomes smaller, the effect is predicted to decrease rapidly and shift towards $x = 0$.

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1 Introduction

In this paper consider the high energy behaviour of the total photoabsorption cross-section combination

$$\sigma_{\gamma p}(\nu, Q^2) = \sigma_T(\nu, Q^2) + \sigma_S(\nu, Q^2)$$

and the associated small x behaviour of the proton structure function, which is given by

$$F_2(x, Q^2) = \frac{Q^2}{4\pi^2\alpha} \sigma_{\gamma p}(\nu, Q^2)$$

for large $\nu \gg 2Mx$. They are conveniently characterised by the Regge pole inspired parameterization

$$\sigma_{\gamma p}(\nu, Q^2) \approx a_P(Q^2)\nu^{\alpha_P-1} + a_R(Q^2)\nu^{\alpha_R-1}$$

which implies

$$F_2(x) \approx \tilde{a}_P x^{1-\alpha_P} + \tilde{a}_R x^{1-\alpha_R} \quad (1)$$

in the scaling region. Interest centres on the observed behaviour of the effective Pomeron intercept α_P . For real photons, the data is consistent with the typical hadronic behaviour [1] $\alpha_P \approx 1.08$ and the same behaviour is consistent [2] with structure function data in the intermediate x -region $0.02 \leq x \leq 0.1$. However experiments at HERA [3, 4, 5] observe a sharp rise in the structure function at small $x < 0.02$ which can be parameterized using an effective intercept $\alpha_P \approx 1.3$ [6]. Theoretical discussion of this effect usually centres on perturbative QCD, and in particular on the prediction $\alpha_P \approx 1.5$ obtained in the leading $\log(1/x)$ approximation [7]. However such discussions are normally restricted to large Q^2 , and can not be easily extended to low Q^2 and real photons. They can not lead to a parameterization valid for all Q^2 , which is required, for example, in calculating radiative corrections; and they can not shed light on the transition between the contrasting

energy dependences observed for real and highly virtual photons, which is one of the most interesting features of the data.

Here we consider a complementary approach suggested by one of us [8] which adopts the laboratory frame viewpoint of hadron dominance models. Such models emphasize the link between real and virtual photons and provide a natural framework for describing the onset of scaling. For example, they give a good description of elastic rho-meson production for both real and highly virtual photons; they provide an interpolation between real photoabsorption and deep inelastic scattering data on protons in the intermediate x -region $0.02 \leq x \leq 0.1$; and they successfully predict the observed shadowing behaviour for real photoabsorption and deep inelastic scattering on nuclei in the same kinematic region¹. The suggestion [8] was that this approach could be extended into the “HERA” region $x \lesssim 0.01$ if observed low x rise is associated with the contribution of high mass fluctuations of the photon which become important at high Q^2 . The discussion centred on the value of the coherence length²

$$l = \frac{2\nu}{m^2 + Q^2} = \frac{1}{Mx} \frac{1}{1 + m^2/Q^2}, \quad (2)$$

which represents the typical distance travelled by a fluctuation of mass m in the laboratory frame. At short coherence lengths, corresponding to large x values $x > 0.1$, these states are essentially bare $\bar{q}q$ pairs and a hadronic component of the photon has not developed. At moderate coherence lengths, corresponding typically to intermediate x values $0.02 < x < 0.1$ for typical masses $m^2 \approx Q^2$, they are assumed to have the single hadron-like behaviour expected for constituent $\bar{q}q$ pairs or vector mesons. However at very small x the photon fluctuations can be very long-lived - for example $l \sim 100 \text{ fm}$ for $x \sim 10^{-3}$ and $m \sim Q^2$ - and it is plausible to assume that they can develop into the hadronic final states observed in e^+e^-

annihilations. For low masses, these can be approximated by a sum of vector mesons; but for high masses complicated multihadron jet-like structures are observed. The proposal [8] was that the afore-mentioned rise in F_2 at small x is associated with just these multihadron states, but only a brief qualitative discussion was given. Here we investigate whether this idea can quantitatively describe both the photoproduction and structure function data in the framework of a simple model. Further, since the nature of the interaction of such complicated intermediate states with the proton is far from clear, we shall assume two simple but contrasting behaviours to see how this affects the fits to the data, and the predictions in the interesting but experimentally unexplored intermediate Q^2 region.

To do this, we adopt a two stage approach. The idea is that the new phenomena are associated with multihadron states which can only play a role for masses $m > m_J$ and coherence lengths l which are greater than some critical values $m > m_J$ and $l > l_c$. By (2) this implies that they are confined to energies

$$\nu > \nu_c \equiv m_J^2 l_c / 2 \quad (Q^2 = 0) \quad (3)$$

in photoproduction, and to the kinematic region

$$x < x_c(Q^2) \equiv \frac{1}{M l_c} \frac{Q^2}{Q^2 + m_J^2} \quad (4)$$

for structure functions. Taking the reasonable values $m_J^2 \approx 10 \text{ GeV}^2$ and $l_c = 10 \text{ fm}$ for example gives $\nu_c = 250 \text{ GeV}$ and $x_c(10 \text{ GeV}^2) = 0.01$. We therefore first formulate a hadron dominance model - the simplest we can think of - and adjust its parameters to fit “pre-HERA” data in regions $\nu < \nu_c$ for $Q^2 = 0$ and $x > x_c(Q^2)$ for $Q^2 \neq 0$; and then introduce the suggested high mass, long coherence length effects to extend it into the new kinematic regions explored by HERA.

¹For recent discussions of these points, and many earlier references, see [8, 9](elastic rho production); [8, 10](real and virtual photoabsorption); and [11, 12](nuclear shadowing).

²For an interesting discussion of the role of the coherence length in another context, see Del Duca, Brodsky and Hoyer [13].

2 The Form of the Parameterization

In the hadron dominance model³, the total cross-section for photoabsorption is given by an expression of the form

$$\sigma_{\gamma p}(\nu, Q^2) = \int dm^2 \int dm'^2 \frac{\rho(m, m', s)}{(m^2 + Q^2)(m'^2 + Q^2)} \quad (5)$$

corresponding to Figure 1. The main contributions are expected to come from elastic and near elastic components in which the two mass values m and m' are not very different. Equation (5) is therefore often replaced by a simple diagonal approximation

$$\sigma_{\gamma p}(\nu, Q^2) = \int_{m_0^2}^{\infty} dm^2 \frac{\rho(\nu, m^2)}{(m^2 + Q^2)^2}, \quad (6)$$

where $\rho(\nu, m^2)$ is an effective quantity, meant to represent a more complicated structure on average. Single hadron-like behaviour of the intermediate states can be incorporated by assuming a Regge-type energy dependence

$$\rho(\nu, m^2) = \rho^P(\nu, m^2) + \rho^R(\nu, m^2) = f_P(m^2)\nu^{\alpha_P-1} + f_R(m^2)\nu^{\alpha_R-1}$$

where $f_P(m^2), f_R(m^2)$ are smoothly varying functions of mass chosen to lead to approximate scaling at large Q^2 . In particular, if we assume

$$\rho^P(\nu, m^2) = a\nu^{\alpha_P-1}(m^2)^{1-\alpha_P} \quad (7)$$

for the dominant diffractive term, we have

$$F_2^P = A x \nu^{\alpha_P} \int_{m_0^2}^{\infty} dm^2 \frac{(m^2)^{1-\alpha_P}}{(m^2 + Q^2)^2} \quad (8)$$

where the parameters m_0 and

$$A = \frac{M a}{2 \pi^2 \alpha}.$$

can be adjusted to fit the data in the “pre-HERA” region. This data has been conveniently parameterized by Donnachie and Landshoff [2] in the form

$$F_2(x, Q^2) = F_2^P + F_2^R$$

$$= A_P x^{1-\alpha_P} \left(\frac{Q^2}{Q^2 + a_P} \right)^{\alpha_P} + A_R x^{1-\alpha_R} \left(\frac{Q^2}{Q^2 + a_R} \right)^{\alpha_R} \quad (9)$$

where

$$\begin{aligned} A_P &= 0.324 & a_P &= 0.562 & \alpha_P &= 1.08 \\ A_R &= 0.098 & a_R &= 0.0111 & \alpha_R &= 0.55. \end{aligned} \quad (10)$$

This form was proposed on purely empirical grounds, but is very similar to parametric forms which have long been used to summarize the predictions of hadron dominance models [14]. Here we replace their F_2^P by the hadron dominance form (8), leaving the Regge component F_2^R , which is very much smaller than the diffractive term in the regions of interest, unchanged. In this way we arrive at the parameterization

$$F_2 = A x \nu^{\alpha_P} \int_{m_0^2}^{\infty} dm^2 \frac{(m^2)^{1-\alpha_P}}{(m^2 + Q^2)^2} + A_R x^{1-\alpha_R} \left(\frac{Q^2}{Q^2 + a_R} \right)^{\alpha_R}. \quad (11)$$

This is a good approximation to the Donnachie-Landshoff form (9, 10) for the choice

$$\alpha_P = 1.08 \quad m_0^2 = 0.518 \text{ GeV}^2 \quad A = 0.633 \text{ GeV}^{1.08} \quad (12)$$

of the parameters associated with the diffractive term, and by implication it gives a good account of the structure function data for $x \gtrsim 0.01$, as illustrated in Figure 2. However, it completely fails to reproduce the HERA data at very small x , as seen in Figure 3, implying a transition region at $x \sim 0.01$ or somewhat lower.

The above approach embodies single hadron-like behaviour $\alpha_P \approx 1.08$ for all intermediate states, and hence for the photoabsorption cross-section and the structure functions. We now modify it by adjusting the contributions from $m > m_J$ and $l > l_c$, which is meant to roughly characterize the region in which single hadron-like behaviour has given way to multihadron-like behaviour for the intermediate states. The behaviour of these states is of course very uncertain and we simply parameterize it by a form similar to (7), but with a, α_P replaced by new parameters a', α' to be

³For reviews, see for example [14] and [8] and references therein.

determined later. In this way we arrive at a representation of the form

$$\begin{aligned} (F_2^p)_{DIFF} &= [\theta(m_j^2 - m^2) + \theta(m^2 - m_j^2)\theta(l_c - l)] \\ &\times A x \nu^{\alpha_P} \int_{m_0^2}^{\infty} dm^2 \frac{(m^2)^{1-\alpha_P}}{(m^2 + Q^2)^2} \\ &+ \theta(m^2 - m_j^2)\theta(l - l_c) A' x \nu^{\alpha'} \int_{m_0^2}^{\infty} dm^2 \frac{(m^2)^{1-\alpha'}}{(m^2 + Q^2)^2}. \end{aligned} \quad (13)$$

which is identical to our previous form (8) in the “pre-HERA” regions $\nu < \nu_c$ ($Q^2 = 0$) and $x > x_c(Q^2)$.

3 Comparison with experimental data

Two types of fit have been explored. In the first (*Fit A*), we impose $\alpha' = \alpha_P = 1.08$ for the high mass, long-lived states, so that the whole of the rise at small x is due to the threshold at $l = l_c$. In the second (*Fit B*) we assign them a steeper energy dependence $\alpha' = 1.27 > \alpha_P$ characteristic of empirical fits of the type (1) at small- x , so that only part of the rise is due to the threshold effect. In both cases, the remaining parameters m_j^2 , l_c and A were adjusted to give a reasonable fit to the HERA structure function data in the range $x < 0.01$ for⁴ $8 \lesssim Q^2 \lesssim 15 \text{ GeV}^2$: essentially, m_j^2 and l_c determine the Q^2 and the x dependence of the low x enhancement, including the threshold $x_c(Q^2)$ by Eq.(4); while A determines its magnitude. The resulting values then used to predict the real photoabsorption cross-section and the structure function in the unexplored region $x < 0.01$, $Q^2 \lesssim 8 \text{ GeV}^2$.

We first consider the recent H1 data [5] at small x , which is consistent with but more precise than the earlier data [3, 4]. Good fits of both types are found corresponding to the parameter values

Fit A : $\alpha' = 1.08$

$$m_j^2 = 16 \text{ GeV}^2 \quad l_c = 15 \text{ fm} \quad A' = 2.7 \text{ GeV}^{-1.08}. \quad (14)$$

⁴We restrict ourselves to $Q^2 \lesssim 15 \text{ GeV}^2$ since we are interested in the transition region from real photons to deep inelastic behaviour. The Donnachie-Landshoff parameterization (9, 10) is a good fit to the intermediate x data in this same Q^2 region, but will of course break down eventually since it gives exact scaling as $Q^2 \rightarrow \infty$.

Fit B : $\alpha' = 1.27$

$$m_j^2 = 8 \text{ GeV}^2 \quad l_c = 6 \text{ fm} \quad A' = 0.62 \text{ GeV}^{-1.08} \quad (15)$$

respectively. These are compared in Figure 3 for $Q^2 = 12 \text{ GeV}^2$, while the predicted Q^2 dependence is shown in Figures 4 and 5. As can be seen, an enhancement of the desired form is obtained, which is confined to small⁵ $x < x_c(m_j, l_c, Q^2)$. Because of this, the fit to the intermediate- x data of Figure 2 is either completely unchanged (*Fit A*) or very slightly modified at the highest Q^2 values for the lowest x values without spoiling the agreement with experiment (*Fit B*) [16].

The corresponding predictions for the real photoabsorption cross-sections [17, 18, 19] are shown in Figure 6. As can be seen, the enhancement from the high mass, long-lived states is confined to high energies and is relatively small. Nonetheless the predictions are a little high compared to the ZEUS data, especially for *Fit B*. The source of this problem is clear: the cross-section that follows from the Donnachie-Landshoff form (9, 10) already completely saturates the experimental high energy cross section. Since our basic vector meson-like contributions have been constructed to reproduce this parameterization, and we have then enhanced them at large masses and large coherence lengths, some disagreement is inevitable. The key point is that if it is not too large, one could hope to correct it by slightly modifying the parameters of the conventional hadron-like contributions, so that they still fit the “pre-HERA” data but do not already saturate the real photoabsorption cross-section at very high energies. One simple but not unique way to do this is to lower α_P slightly, and then repeat the analysis.

Since we follow the same procedure as before, we shall summarize it rather briefly.

The pre-HERA data is still well fitted if the parameters in the Donnachie-Landshoff

⁵Because we have for simplicity used θ -functions to separate the different regions in (13), there is a discontinuity in the derivative of $F_2(x)$ at $x = x_c$. This could easily be smoothed slightly by using gentler thresholds, but given the accuracy of the data, this is not necessary.

form (9) are replaced by:

$$\begin{aligned} A_P &= 0.350 & a_P &= 0.530 & \alpha_P &= 1.06 \\ A_R &= 0.073 & a_R &= 0.010 & \alpha_R &= 0.55 . \end{aligned} \quad (16)$$

Again we retain the Regge component F_2^R but replace the dominant diffractive component F_2^D by a hadron dominance representation (8) with parameters

$$\alpha_P = 1.06 \quad m_0^2 = 0.499 \text{ GeV}^2 \quad A = 0.679 \text{ GeV}^{1.06}. \quad (17)$$

We then modify the behaviour of the heavy, long-lived states in accordance with our final representation (13) and obtain two different fits as before corresponding to the parameter values:

Fit A' : $\alpha' = 1.06$

$$m_J^2 = 16 \text{ GeV}^2 \quad l_c = 15 \text{ fm} \quad A' = 3.2 \text{ GeV}^{1.06}. \quad (18)$$

Fit B' : $\alpha' = 1.27$

$$m_J^2 = 8 \text{ GeV}^2 \quad l_c = 5 \text{ fm} \quad A' = 0.64 \text{ GeV}^{1.27} \quad (19)$$

respectively. The corresponding fits to the structure function data at low x are shown in Figures 7 and 8, and are very similar to our previous fits *A* and *B*. However the predictions for real photoabsorption are now in good agreement with the data, as shown in Figure 9.

4 Summary

Real photoabsorption and proton structure function data at small x exhibit very different energy dependence at fixed Q^2 . Here we have shown that both can be well described by a simple hadron dominance model in which the striking enhancement observed at HERA at very low x and high Q^2 is attributed to contributions from heavy long-lived fluctuations of the incoming photon. Two contrasting assumptions

on the energy dependence of the scattering of these states by the proton have been made, leading to fits which differ at very small $x \lesssim 10^{-4}$ as can be seen in Figure 3. However they are very similar for the range $2 \cdot 10^{-4} < x \lesssim 2 \cdot 10^{-3}$ and $Q^2 \lesssim 8 \text{ GeV}^2$, in which the well-known small x enhancement has been observed at HERA. The most important predictions concern the behaviour of this enhancement in the intermediate Q^2 range $0 < Q^2 \lesssim 6 \text{ GeV}^2$, which has not yet been explored experimentally. The fits give similar results for this Q^2 dependence in the relevant x region $2 \cdot 10^{-4} < x \lesssim 2 \cdot 10^{-3}$, as can be seen by comparing Figures 4 and 5; and as Q^2 becomes smaller, the effect is predicted to decrease rapidly and shift towards $x = 0$,

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Figure Captions

Figure 1 The hadron dominance model Eq.(5).

Figure 2 Comparison of the structure function data [15] at intermediate x with the form (8,12) for the diffractive part, together with the Regge contribution from (9).

Figure 3 Fits to the H1 data [5] at $Q^2 = 12 GeV^2$ corresponding to fits A(solid line) and B(dashed line). The Donnachie-Landshoff parameterization (9, 10) is shown for comparison (dotted line).

Figure 4 Predicted structure function at small x corresponding to Fit A. The data [5] correspond to $Q^2 = 15 GeV^2$ (solid circles) and $Q^2 = 8.5 GeV^2$ (open circles) and the curves(from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and $1 GeV^2$ respectively.

Figure 5 Predicted structure function at small x corresponding to Fit B. The data [5] correspond to $Q^2 = 15 GeV^2$ (solid circles) and $Q^2 = 8.5 GeV^2$ (open circles) and the curves(from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and $1 GeV^2$ respectively.

Figure 6 Fits to the real photoabsorption data corresponding to fits A(solid line) and B(dashed line).The Donnachie-Landshoff parameterization (9, 10) is shown for comparison (dotted line).

Figure 7 Predicted structure function at small x corresponding to Fit A'. The data [5] correspond to $Q^2 = 15 GeV^2$ (solid circles) and $Q^2 = 8.5 GeV^2$ (open circles) and the curves(from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and $1 GeV^2$ respectively.

Figure 8 Predicted structure function at small x corresponding to Fit B'. The data [5] correspond to $Q^2 = 15 GeV^2$ (solid circles) and $Q^2 = 8.5 GeV^2$ (open circles) and the curves(from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and $1 GeV^2$ respectively.

Figure 9 Fits to the real photoabsorption data corresponding to fits A'(solid line) and B'(dashed line). The modified Donnachie-Landshoff parameterization (9, 16) is shown for comparison (dotted line).

Figure 1: The hadron dominance model Eq.(5).

Figure 2: Comparison of the structure function data [15] at intermediate x with the form (8,12) for the diffractive part, together with the Regge contribution from (9).

Figure 3: Comparisons of the H1 data [5] at $Q^2 = 12 \text{ GeV}^2$ corresponding to fits A(solid line) and B(dashed line). The Donnachie-Landshoff parameterization (9, 10) is shown for comparison (dotted line).

Figure 4: Predicted structure function at small x corresponding to Fit A. The data [5] correspond to $Q^2 = 15 \text{ GeV}^2$ (solid circles) and $Q^2 = 8.5 \text{ GeV}^2$ (open circles) and the curves (from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and 1 GeV^2 respectively.

Figure 5: Predicted structure function at small x corresponding to Fit B. The data [5] correspond to $Q^2 = 15 \text{ GeV}^2$ (solid circles) and $Q^2 = 8.5 \text{ GeV}^2$ (open circles) and the curves (from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and 1 GeV^2 respectively.

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Figure 8: Predicted structure function at small x corresponding to Fit B' . The data [5] correspond to $Q^2 = 15 \text{ GeV}^2$ (solid circles) and $Q^2 = 8.5 \text{ GeV}^2$ (open circles) and the curves (from the top down) to $Q^2 = 15, 8.5, 5, 2.5$ and 1 GeV^2 respectively.

Figure 9: Fits to the real photoabsorption data corresponding to fits A' (solid line) and B' (dashed line). The modified Donnachie-Landshoff parameterization (9, 16) is shown for comparison (dotted line).