April 23rd,1993

Revised June 21st, 1993

MC-TH-93/09-REV

MC-TH-93-09 Rev

Fermilab Library
0 1160 0025804 0

The hadron-like component of the photon and nucleon structure functions at small x

Graham Shaw

Department of Physics

University of Manchester

M13 9PL

ABSTRACT

Recent experimental data on exclusive ρ meson production and on nuclear shadowing strikingly confirm the predictions of hadron dominance at small x but high $Q^2 \gg m_\rho^2$. Its implications at very high energies are compatible with recent data from HERA on both real photoabsorption and the behaviour of structure functions at small-x but large Q^2 values. Data at intermediate Q^2 will be crucial in testing this interpretation.

FERMILAB
JUL 15 1993
LIBRARY

The hadron-like component of the photon and hadron dominance are long-standing ideas which are compatible with and complementary to approaches based on the parton model in appropriate kinematic regions. At low $Q^2 < m_\rho^2$ hadron dominance provides a direct explanation for the observed similarities between the energy dependencies, forward peaks and nuclear shadowing effects observed in photoproduction and strong interaction processes at high energies. Until recently, however, there was very little evidence for these characteristic features of hadron-like behaviour in leptoproduction processes at low-x but high Q^2. Indeed, early data[1] on the leptoproduction of rho-mesons seemed to disagree with the predictions of hadron dominance, giving rise to a widespread view that the hadron-like behaviour at small-x was purely a low Q^2 phenomenon. Here we point out that recent data on vector meson production [2] and nuclear shadowing [3,4] strikingly confirm the predictions of hadron dominance at large Q^2; and comment on its implications for the small-x behaviour of structure functions[5] and the total photon absorption cross-section[6], at HERA. Firstly, however, we briefly discuss the possible existence and nature of a hadron-like component of the photon in various kinematic regions.

The hadron-like component of the photon

This is best understood by considering the laboratory frame, in which the photon is envisaged as dissociating into bare quark-antiquark pairs which evolve according to QCD before interacting with the hadron target. In models which give rise to scaling, the masses m_f of the dominant fluctuations satisfy

$$m_f^2 \lesssim Q^2 \tag{1}$$

so that their coherence lengths

$$l_f = \frac{2\nu}{m_f^2 + Q^2} = \frac{1}{xM}\,\frac{1}{(1 + m_f^2/Q^2)} \sim \frac{1}{2xM}\ . \tag{2}$$

At small x, these become large compared to the typical length scale of the strong interaction, and it is reasonable to assume that the fluctuations develop hadron-like

properties. This is the hadron-like component of the photon and its nature will depend on both x and Q^2. It will be useful in what follows to keep four diffrerent kinematic regions in mind. The distinction between these various regions will not be sharp, and the x and Q^2 values chosen to define them are only intended as a rough but reasonable guide.

Region I $x \lesssim 0.01 \quad Q^2 \lesssim 4GeV^2$.

The coherence lengths are very long indeed - of order 100 f at $x \sim 10^{-3}$ for example - and the pairs can develope into the hadronic states observed in electron - positron annihilation. In view of eq.(2) it is reasonable to approximate these by a sum of vector mesons in this Q^2 range.

Region II $x \lesssim 0.01 \quad Q^2 \gtrsim 4GeV^2$.

As Q^2 increases, the complicated jet-like multi-hadron states observed in electron-positron annihilation at high energies will play an increasingly important role.

Region III $0.01 \lesssim x \lesssim 0.1$

At $x \sim 0.05$ the coherence length is of order 2f. In this region it is plausible that the quarks have time to clothe themselves, but not to develope into the asymptotic hadron states observed in electron-positron annihilation. In other words a description in terms of "constituent" quark-antiquark pairs might be more appropriate.

Region IV $x \gtrsim 0.1$

In this region the typical coherence length is less than 1f and the hadron-like component of the photon disappears.

The hadron dominance model

The hadron dominance model of soft photo-processes rests on two main assumptions. Firstly the hadron-like component of the photon is assumed to dominate over contributions from short lived fluctuations with small coherence lengths and from "direct" processes in which the photon is absorbed by a quark constituent of the

nucleon[1]. Secondly the hadron-like nature of the intermediate states is embodied in their scattering amplitudes on nucleons, which are assumed to have the same properties as high energy hadron-nucleon scattering amplitudes: large slowly varying total cross-sections, almost purely imaginary elastic scattering amplitudes, sharp forward peaks, etc. This would be satisfied for vector mesons, constituent quark-antiquark pairs[2] or a hadronic continuum, and is a reasonable assumption provided we restrict ourselves to kinematic regions I and III. For real photons ($Q^2 = 0$) the biggest contributions are associated with the lightest vector mesons ρ, w and ϕ, although corrections from heavier states are not negligible. At large Q^2 the heavier states become more important, and their contibutions can be adjusted to lead to approximate scaling behaviour[7,8]. In this way one arrives at models which provide a natural interpolation between $Q^2 = 0$ and the large Q^2 region, where they are dual to the covariant parton model[9].

In what follows, we will consider isovector photons only and for simplicity, approximate the continuum of possible intermediate states by a tower of vector mesons $V_0 = \rho, V_1, V_2, ...V_n...$ of increasing masses m_n with $\gamma - V_n$ couplings e/f_n. The forward scattering amplitudes for virtual Compton scattering and transverse rho-meson production are then given by the familiar generalised vector dominance (GVD) expressions[10]

$$Im\, f_{\gamma\gamma}(s_1 Q^2) = \sum_{n,m} \frac{e}{f_n} \frac{m_n^2}{m_n^2 + Q^2} Im f_{nm}(s) \frac{m_m^2}{m_m^2 + Q^2} \frac{e}{f_m} \tag{3}$$

and

$$Im f_{\gamma\rho}(s, Q^2) = \sum_n \frac{e}{f_n} \frac{m_n^2}{m_n^2 + Q^2} Im f_{no}(s)\,. \tag{4}$$

Here the $f_{nm}(s)$ are the forward amplitudes for elastic scattering ($m = n$) and

[1]We stress that this classification is based on the laboratory frame as opposed to the infinite momentum frame. In a relativistic collision there is of course no unambiguous, frame independent way of distinguishing fragments of the beam and target from each other or from particles created in the collision.

[2]In the additive quark model, the vector meson scattering amplitudes are of course just the sum of the constituent quark scattering amplitudes.

diffraction dissociation ($m \neq n$) processes, which are assumed to have the typical properties of hadronic interactions listed above[3]. In particular, they are assumed to have the characteristic energy dependence

$$Imf_{nm}(\nu) = a^P_{nm}\nu^{\alpha_P} + a^R_{nm}\nu^{\alpha_R} \tag{5}$$

of hadronic processes, where the Pomeron and Regge intercepts have the values

$$\alpha_P \approx 1.08 \quad \alpha_R \approx 0.55 \tag{6}$$

determined from a recent extensive analysis[11] of hadron total cross-section data. This is a plausible assumption in kinematic regions I and III as indicated above. In the following sections we will confine ourselves to just these regions before turning to the more problematic region II at the end of the paper.

Rho-meson production

We first consider the reaction

$$\mu^- + p \rightarrow \mu^- + \rho^0 + p\,, \tag{7}$$

which is conveniently regarded as virtual photoproduction. The well-known predictions of rho dominance at low Q^2 correspond to retaining only the terms with $m = n = 0$ in equation (4), while the corrections to rho-dominance arise from the diffraction dissociation amplitudes f_{on} with $n \neq 0$. Such diffraction dissociation or 'off-diagonal' terms are vital to the consistency of the hadron dominance scheme, and must interfere destructively with the elastic or 'diagonal' terms if the model is to be consistent with approximate scaling in electron-positron annihilation and deep inelastic scattering [7]. They are further restricted by requiring that they have similar characteristics to those observed in pion initiated diffraction dissociation processes. This was the approach adopted by Fraas, Read and Schildknecht[12], who

[3]Not all GVD models are hadron dominance models. In so-called *diagonal GVD* models diffraction dissociation is neglected and the total cross-sections for the heavier states are assumed to be very small compared to typical hadron cross-sections.(Cf. reference 10)

assumed on this basis that diffraction dissociation cross-sections have very sharp forward peaks and are largest for transitions between states which are close in mass. This led to corrections to simple vector dominance that were small for real photons, but increased rapidly with increasing Q^2. Furthermore, the resulting predictions have two characteristic features that arise essentially from the destructive nature of the interference between the diffraction dissociation and elastic components, independent of the details of the model. The first is that the cross-section for transverse rho production should fall off more rapidly than rho-dominance predicts, being given approximately by

$$\frac{d\sigma}{dt}(Q^2)|_{t=0} \approx \left(\frac{\tilde{m}^2}{\tilde{m}^2 + Q^2}\right)^2 \frac{d\sigma}{dt}(Q^2 = 0)|_{t=0} \tag{8}$$

where $\tilde{m}$ is less than the rho-mass.. Specifically, reasonable assumptions led to the range of values $0.4m_\rho^2 \lesssim \tilde{m}^2 \lesssim 0.75m_\rho^2$. The second predicion concerns the slope parameter B defined by

$$\frac{d\sigma}{dt} = Ae^{-Bt} \tag{9}$$

for small t. This was predicted to fall from a value of order $6 - 8\,GeV^{-2}$ in photoproduction to a value of order $4 - 6\,GeV^{-2}$ in electroproduction by $Q^2 \sim 2\,GeV^2$.

The above predictions were made in 1975, but were not tested experimentally until 1985. The European Muon (EMC) collaboration[1] then found that the cross-section indeed fell off faster than simple vector dominance, while the slope parameter B fell to a value of order $1\,GeV^{-2}$ at a Q^2 values of order $10\,GeV^2$. This value is so small that the authors concluded that the production mechanism in this region was a "non-diffractive hard scattering process" and that the "soft hadron-like properties of the photon" had disappeared.

Recent measurements[2] with higher statistics by the successor New Muon (NMC) collaboration do not corroborate this result. When similar cuts and selections were used in the data analysis, the results agreed with those of the earlier

experiment. However the increased statistics enable the uncertainties associated with the background of non-exclusive rho-production events to be greatly reduced. When this was done they found that the slope parameter still decreased from its value at $Q^2 = 0$, but only to a value[4] of $4.3 \pm 0.6 \pm 0.7 GeV^2$ for Q^2 of order 10 GeV^2. The authors point out that this corresponds to a much sharper distribution than that observed in the inclusive production of leading hadrons in deep inelastic scattering. Here we note their results agree well with the long-standing predictions of hadron dominance, and are clear evidence for hadron-like behaviour at large Q^2.

Nuclear shadowing in deep inelastic scattering

Shadowing arises naturally in hadron dominance models because the mean free paths of hadrons in nuclear matter are typically much smaller than nuclear radii. In addition, a fluctuation f can only contribute to shadowing if its coherence length l_f is bigger than its mean free path λ_f, so that appreciable absorption can occur. Using (2) this gives

$$x \lesssim 1/2M\lambda_f = 1/2M\rho\sigma_f$$

where ρ is the nuclear density and σ_f are the corresponding total cross-sections on nucleons. These are assumed to be only weakly dependent on the mass of the intermediate state for fixed internal quantum numbers, leading to the predictions that shadowing is confined to the small-x region, and is only weakly dependent on Q^2 at fixed-x[5]. That is, it approximately scales.

This predicted behaviour was first obtained in hadron dominance models in 1976[8], but was not observed experimentally until 1988[15]. This has been confirmed by subsequent experiments[16] and in particular the model accounts quantitatively[14] for recent experimental data which is of unprecedented accuracy[3] and which extends to unprecedentedly small values of x[4]. This shadowing data extends to Q^2 values of order 5 GeV^2 and is further evidence for hadron-like behaviour at

[4]They actually work in terms of p_T^2 rather than t, but this is not important for exclusive events.
[5]This is discussed more explicitly in references 13 and 14

large $Q^2 \gg m_\rho^2$.

Shadowing effects can also arise from perturbative QCD effects, but these are too small to account for the data[17]. We emphasise again that hadron dominance is perfectly compatible with phenomenological parton models, which can also account for shadowing. Indeed the distinction between the two is often somewhat artificial; for example, when the partons are assumed, like hadrons, to scatter from nucleons via "non-perturbative" Pomeron exchange[18].

Real photoabsorption

Before discussing structure functions at small-x values, it will be convenient to briefly summarise the energy dependence of the real photo-absorption cross-section σ_γ. In hadron dominance models, this follows directly from equations (3) and (5), implying

$$\sigma_\gamma \simeq a_P^\gamma \nu^{\alpha_P - 1} + a_R^\gamma \nu^{\alpha_R - 1} \tag{10a}$$

$$\simeq a_P^\gamma \nu^{0.08} + a_R^\gamma \nu^{-0.45} \tag{10b}$$

where the Pomeron and Regge intercepts have the values given in eq.(6). This behaviour is well established. In particular, Donnachie and Landshoff [11] have obtained a good fit to real photo-absorption data at centre of mass energies below 20 GeV using this parameterisation, and a massive extrapolation of this fit to high energies is in good agreement with the recent HERA data[6].

Nucleon structure functions at small-x

To begin with we restrict ourselves to region III

$$0.01 \lesssim x \lesssim 0.1$$

where the simple hadronic behaviour (5) and (6) should be a good approximation for the typical intermediate states at all Q^2. Equations (3) and (5) together with the optical theorem then lead to an expression of the form

$$F_2(\nu, Q^2) \simeq a_P(Q^2)\nu^{\alpha_P - 1} + a_R(Q^2)\nu^{\alpha_R - 1} \tag{11a}$$

$$\simeq a_P(Q^2)\nu^{0.08} + a_R(Q^2)\nu^{-0.45} \,. \tag{11b}$$

The values of the functions $a_P(Q^2), a_R(Q^2)$ depend on the assumed values of the couplings e/f_n and the coefficients a^P_{mn}, a^R_{mn} and the interest in specific hadron dominance models is often focused on their use to interpolate from photoproduction ($Q^2 = 0$) to the scaling region [6] Here we focus on the large Q^2 behaviour, where the results

$$F_2(x) \simeq a_P x^{1-\alpha_P} + a_R x^{1-\alpha_R} \tag{12a}$$

$$\simeq a_P x^{-0.08} + a_R x^{0.45} \tag{12b}$$

follow directly from (11) and (6) for any values of couplings and coefficients which lead to approximate scaling[7]. This result is well-known and has been built into many parton models and structure function analyses in this region.

We finally turn to the behaviour of the structure functions at very small values $x \lesssim 0.01$. For $Q^2 \lesssim 4GeV^2$ (region I), the assumed high energy behaviour (5,6) should be a good approximation and eq.(11) should still hold. However for $Q^2 \gtrsim 4GeV^2$ (region II) multi-hadron intermediate states should become increasingly important. Hence the assumption of single hadron-like behaviour becomes unreliable so that the derivation of (11) breaks down. In contrast, arguments based on extensions of perturbative QCD lead to the more dramatic prediction

$$F_2(x) \sim x^{1-\alpha} \quad \alpha \sim 1.5 \tag{13}$$

associated with the so-called "perturbative Pomeron"[19] as the dominant behaviour at small x values[8], and this is at least qualitatively supported by recent data from

[6]Such detailed discussions[7,8] usually assume $\alpha_P = 1$ and $\alpha_R = 1/2$. Their extension to incorporate more up-to-date values of these exponents, and the resulting comparison with recent low and intermediate Q^2 data, will be discussed elsewhere.

[7]The argument extends trivially to a continuum of intermediate states, when the sums in (3) and (4) are simply replaced by integrals.

[8]This behaviour is expected to be softened by gluon saturation effects, but only at extremely small x values[20].

HERA[5]. This is compatible with our previous arguments provided that this behaviour only dominates in the limited region $x \lesssim 0.01$; and that the switch-over from the $\alpha_P \sim 1.08$ behaviour (10,11) observed in real photo-absorption to the predicted $\alpha \sim 1.5$ behaviour (13) at large Q^2 occurs relatively slowly in order to be approximately compatible with (11) for $Q^2 \lesssim 4GeV^2$. Data at such intermediate Q^2 values will clearly be of considerable interest.

References

1. J.J. Aubert et. al.(EMC collaboration), Phys. Lett. **161B** (1985) 203.
2. P. Amaudruz et al (NMC collaboration), Z. Phys. **C54** (1992) 239
3. P. Amaudruz et al (NMC collaboration), Z. Phys. **C51** (1991) 387
4. M.R. Adams et al (E665 collaboration), Phys. Rev. Lett. **68** (1992) 3266
5. H1 collaboration, presented by A. de Roeck at a meeting of the U.K. Phenomenology Initiative, Durham, 1993(to be published).
6. N.H. Brook et. al. (ZEUS collaboration) Phys. Lett. **B293** (1992) 465; T.Ahmed et. al.(H1 collaboration) Phys. Lett. bf B299 (1993) 374
7. H. Fraas, B.J. Read and D. Schildknecht, Nucl. Phys. **B86** (1975) 346
8. P. Ditsas and G. Shaw, Nucl. Phys. **B113** (1976) 246
9. S.J. Brodsky,G. Grammer Jr., P. Lepage and J.D. Sullivan(unpublished, 1978); this work is described by G. Grammer Jr. and J.D. Sullivan in "Electromagnetic Interactions of Hadrons" vol. 2, ed.A. Donnachie and G. Shaw, Plenum Press, New York 1978. (Cf. section 2.1.3) and summarised in reference 13 below.
10. For a review, see A. Donnachie and G. Shaw in 'Electromagnetic Interactions of Hadrons', Vol. 2, ed. A. Donnachie and G. Shaw (Plenum, New York, 1978)
11. A. Donnachie and P.V. Landshoff, Phys. Lett. **B296** (1993) 227
12. H. Fraas, B.J. Read and D. Schildknecht, Nucl. Phys. **B88** (1975) 301
13. G. Shaw, Phys. Lett. **B226** (1989) 125
14. G. Shaw, Phys. Rev. **D47** (1993) R3676

15. M. Arneodo et al.(EMC Collaboration) Phys. Lett. **B211** (1988) 493
16. A useful tabulation of data on shadowing in deep inelastic scattering prior to 1991 is given by R.G.Roberts and M.R.Whalley, J.Phys.**G17**,D1(1991)
17. Yu. l. Dokshitzer, V. A. Khoze, A. H. Mueller and S. I. Troyan, 'Basics of Perturbative QCD ' Editions Frontieres ', Paris(1991) Cf. chapter 8 and references therein.
18. For a review of shadowing, with extensive references to the various theoretical models, see M. Arneodo, CERN-PPE/92-113(to be published in Phys. Rep.)
19. Y.Y. Bulitsky and L.N. Lipatov, Sov. J. Nucl. Phys. **28** (1978) 822; E.A. Kuraev, L.N. Lipatov and V.S. Fadin, Sov. Phys. JETP, **45** (1977) 199
20. L. V. Gribov, E. M. Levin and M. G. Ryskin, Phys.Rep. **100** (1983) 1; A.H. Mueller and J. Qiu, Nucl. Phys. **B268** (1986) 427