SCALING VIOLATION IN ELECTROPRODUCTION AT LARGE ω'

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The GVD predictions for scaling violation in electroproduction at $\omega' \gtrsim 5$ are presented and agree with data. The effects of charm are included and found negligible in the $\omega' - q^2$ domain of present experiments, but appreciable at higher ω' and (or) q^2.

The first experimental results on the expected [1] Scaling Violation (SV) in electroproduction [2–5] and neutrino production [6] have already appeared in the literature. They indicate that $F_2(\omega', q^2) \equiv \nu W_2(\omega', q^2)$, as a function of q^2, approaches the scaling limit from *above* for [2] $1.5 \lesssim \omega \lesssim 3$, and from *below* for [2–5] $5 \lesssim \omega$. Obviously this is evidence against a common functional form like [7] $N/(1+q^2/\Lambda^2)^2$ for the approach to scaling at any fixed ω. On the other hand, the experimental results are in qualitative agreement with the predictions of the asymptotically free gauge theories [8, 5]. We show below that they are in quantitative agreement with Generalized Vector Dominance (GVD) as well.

Some time ago a formulation of (GVD) was given [9, 10], which makes it consistent and complementary to the Parton Model (PM) for electroproduction in the scaling region. GVD may then be used to calculate the Pomeron and f-A_2 contributions to the parton distributions, and to the deep inelastic structure functions. The advantage of the combined use of PM and GVD is that we now have specific constraints on the parton distributions for large $\omega = 1/x$. GVD gives additional information though. It supplies a Regge representation for the nucleon structure functions valid for *large* W^2, and, *any* q^2. It therefore predicts a definite approach to scaling as q^2 increases, for fixed and large ω'. Our aim in the present note is to give these predictions, compare with existing data [2–5], and discuss their implications for the forthcoming ones.

In the high ω' regime, there are essentially two types of SV. The first is induced by the ordinary components of the electromagnetic current and disappears quite fast with q^2; (i.e. for $q^2 \approx 2$ GeV^2). The second is related to the new components of the electromagnetic current which are considered responsible [11, 12] for the appearance of the ψ-resonances [13] in e^+e^-, and for the large values of $\sigma(e^+e^- \to \text{hadrons})$ at $\sqrt{s} \gtrsim 4$ GeV. One of the most common attitudes towards these, is to assume a charm contribution (j^c_μ) to the electromagnetic current

$$j^{\mathrm{em}}_\mu = j^3_\mu + \frac{1}{\sqrt{3}} j^8_\mu + \frac{2}{3} j^c_\mu, \tag{1}$$

and to assign a $c\bar{c}$ quark structure to the ψ-resonances, called here φ_c's. We view the charm current as the cause of the second type of SV, which is characterized by a very slow vanishing with q^2. We remark that the two types of SV are quite distinct. They are studied in detail below.

The model: GVD gives the Pomeron and f-A_2 Regge exchange contributions to the proton structure functions. Based on U(4) asymptotic symmetry for the current propagator, which has been found to be in agreement with experiment [11] and appealing theoretically [14], we have [9]

$$F_{1\mathrm{p}}(\omega', q^2) \equiv 2MW_{1\mathrm{p}}(\omega', q^2)$$

$$= \frac{\sigma_{\mathrm{D}}(\rho\mathrm{p})}{9\pi\alpha_\rho f^2_\rho} \{10 B_\rho(1, q^2) + \frac{2}{r} B_\varphi(1, q^2)$$

$$+ \frac{8}{r_\mathrm{c}} B_{\varphi\mathrm{c}}(1, q^2)\} (2M\nu - q^2) +$$

$$+\frac{4}{3}\,\frac{\sigma_{\mathrm{R}}(\rho\mathrm{p})(2M\nu)^{1/2}}{\pi\alpha_{\rho}f_{\rho}^{2}}\,B_{\rho}(1/2,\,q^{2})(2M\nu-q^{2})^{1/2} \tag{2}$$

The ratio $R(q^2, W) \equiv \sigma_{\mathrm{L}}/\sigma_{\mathrm{T}}$ satisfies

$$\lim_{q^2\to 0} R(q^2, W) = 0, \tag{3a}$$

and

$$R(q^2, W) = g(q^2), \tag{3b}$$

for large W^2. If Pomeron couples to longitudinal as well as to transverse photons, in the off shell Compton amplitude, then $g(q^2) \neq 0$. Otherwise[‡1] $g(q^2) = 0$. Present experimental data agree with [3, 4]

$$R(q^2, W) \approx 0.18 \tag{3c}$$

for $q^2 \geqslant 0.1\ \mathrm{GeV}^2$, $W > 2$ GeV. Above we used

$$\omega' = \omega + \frac{M^2}{q^2} = \frac{2M\nu + M^2}{q^2}, \quad W^2 = q^2(\omega' - 1), \tag{4}$$

the Pomeron and Regge exchange contributions to the ρ-p total cross section [17]

$$\sigma_{\mathrm{D}}(\rho\mathrm{p}) = 23 \pm 3\ \mathrm{mb}, \quad \sigma_{\mathrm{R}}(\rho\mathrm{p}) = \frac{(10\pm 2)\mathrm{mb\ GeV}^{1/2}}{\sqrt{\nu}}, \tag{5a, b}$$

and the GVD functions

$$B_{\mathrm{V}}(\alpha, q^2) = a_{\mathrm{V}} \sum_{n=0}^{\infty} \frac{(1 + a_{\mathrm{V}}n)^{1-\alpha}}{[q^2/m_{\mathrm{V}}^2 + 1 + a_{\mathrm{V}}n]^2}, \tag{6a}$$

where V stands for ρ, φ, φ_{c} and [2, 11]

$$a_\rho = 2, \quad a_\varphi = 1.6, \quad a_{\mathrm{c}} = 0.42 \tag{6b}$$

define the spacings of the ρ-, φ- and φ_{c}-like mesons. For the ratios of the diffractive cross sections of the various vector mesons we have [15]

$$\frac{1}{r} \equiv \frac{\sigma_{\mathrm{D}}(\varphi\mathrm{p})}{\sigma_{\mathrm{D}}(\rho\mathrm{p})} \approx 0.5, \quad \frac{1}{r_{\mathrm{c}}(W)} \equiv \frac{\sigma_{\mathrm{D}}(\varphi_{\mathrm{c}}\mathrm{p}, W^2)}{\sigma_{\mathrm{D}}(\rho\mathrm{p})}. \tag{7a, b}$$

Finally we note that $\sigma_{\mathrm{D}}(\varphi_{\mathrm{c}}\mathrm{p}, W^2)$ should vanish at threshold and satisfy

$$1/r_{\mathrm{c}} = m_\rho^2/m_{\varphi_{\mathrm{c}}}^2 \tag{8a}$$

much above it. This result is obtained [9] by using GVD to calculate the pomeron contribution to the parton distribution, and then demanding SU(4) symmetry for these distributions[‡2]. It differs somewhat from the prediction derived on the basis of the tensor dominated pomeron dynamics and SU(4) symmetry for the Tensor-Vector-Vector (TVV) couplings [16], which is

$$1/r_{\mathrm{c}} = (\alpha'_\rho/\alpha'_{\varphi_{\mathrm{c}}})\, m_\rho^2/m_{\varphi_{\mathrm{c}}}^2 \tag{8b}$$

at high energies. Here α'_ρ and α'_φ are the slopes of the ρ and φ_{c} trajectories respectively, and satisfy [9]

$$\alpha'_\rho/\alpha'_{\varphi_{\mathrm{c}}} = a_{\mathrm{c}} m_{\varphi_{\mathrm{c}}}^2 / a_\rho m_\rho^2 = 3.4.$$

The difference between (8a) and (8b) should probably be attributed to the SU(4)-breaking in the TVV couplings and/or in the parton distributions at small x. In our calculations below we use (8a) which is more consistent with our approach and in better agreement with experiment. But our results are easily modified for any other assumption about the asymptotic value of $r_{\mathrm{c}}(W)$. Present experimental data suggest that $\sigma_{\mathrm{D}}(\varphi_{\mathrm{c}}\mathrm{p}, W^2)$ is very small for [17] $W^2 \lesssim 20\ \mathrm{GeV}^2$ and consistent with (8a), (7b) at [18] $W^2 \approx 150-200\ \mathrm{GeV}^2$. In the intermediate energy region

$$20\ \mathrm{GeV}^2 \lesssim W^2 \lesssim 150\ \mathrm{GeV}^2, \tag{9}$$

$\sigma_{\mathrm{D}}(\varphi_{\mathrm{c}}\mathrm{p}, W^2)$ should rise smoothly [19]. These results are consistent with the parametrization

$$\sigma_{\mathrm{D}}(\varphi_{\mathrm{c}}\mathrm{p}, W^2) = \{(m_\rho^2/m_{\varphi_{\mathrm{c}}}^2)\,\sigma_{\mathrm{D}}(\rho\mathrm{p})\} \times \mathrm{th}^2\,(0.0176|W^2 - M^2|), \tag{10}$$

which approaches its asymptotic value (8a) at $\sim 200\ \mathrm{GeV}^2$ and is used below the estimate the charm contribution to electroproduction. The sensitivity of our calculations to the detailed form of (10) is also discussed.

Results. We first discuss those results which are relevant for the present experimental data [2–5]. These data correspond to low values of W^2 where $\sigma_{\mathrm{D}}(\varphi_{\mathrm{c}}\mathrm{p}, W^2)$ is neglible, and the new components of the electromagnetic current, (whether charm or anything else), completely irrelevant. Therefore present

‡1 In the simplest GVD version, which is consistent with the simplest PM, we have $g(q^2) = 0$ and $R(q^2, W) = q^2/\nu^2$ (See ref. [9]).

‡2 See eqs. (24, 25) of ref. [9].

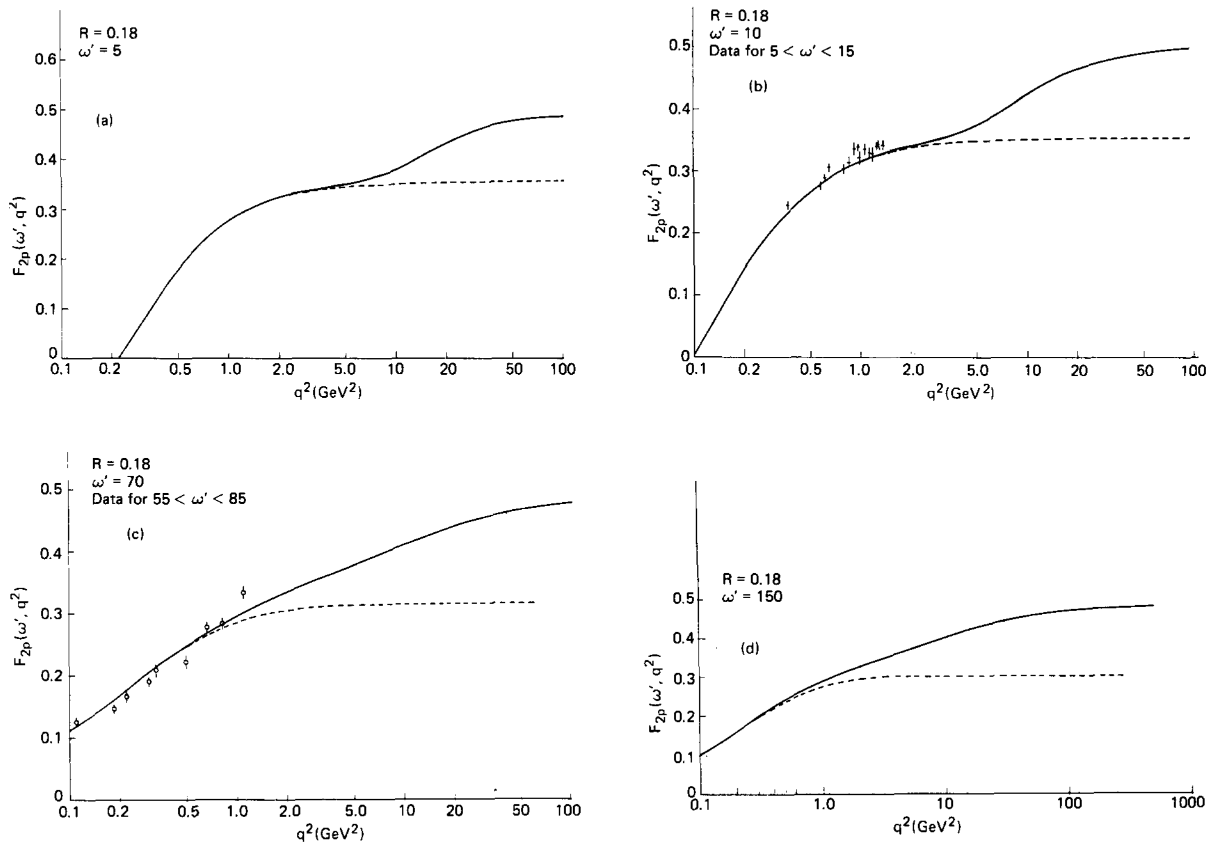

Fig. 1. $F_{2p}(\omega', q^2) \equiv \nu W_{2p}(\omega', q^2)$ as a function of q^2 for $\omega' = 5, 10, 70, 150$. The experimental data are from ref. [4] and correspond to $5 \lesssim \omega' < 15$ in b, and $55 < \omega' < 85$ in c. Broken lines give the contribution of the ordinary components of the electromagnetic current. Solid lines include also the contribution of a possible charm component to this current.

experimental data study only the SV due to the *ordinary* components of the electromagnetic current.

Using (2)–(7) we give in fig. 1 the GVD predictions for the SV in $F_{2p}(\omega', q^2)$ at $\omega' \gtrsim 5$. The broken lines give the contribution of the *ordinary* components of the electromagnetic current and indicate that the induced SV vanishes already at $q^2 \sim 1-2$ GeV^2 for $\omega' \geqslant 5$. These predictions are in good agreement with the data of refs. [4, 2] which show that the electroproduction structure functions rise to their scaling limit at $\omega' \geqslant 5$. They are also consistent with the results of Fox et al. [5], although no detailed statement can be made in this case since our theory is not valid [9] for $\omega < 5$.

Finally we turn to the results of Stein et al [3]. A kind of factorization for the approach to scaling was observed in this experiment. To explain it let us write,

$$F_{2p}(\omega', q^2) = D(\omega', q^2)\ \{1 - W_2^{el}(q^2)\} \tag{11}$$

$$W_2^{el}(q^2) = \frac{G_E^2(q^2) + \tau G_M(q^2)}{1+\tau}\,, \quad \tau = \frac{q^2}{4M^2} \tag{12}$$

where G_E, G_M are respectively the elastic, electric and magnetic form factors of the proton. It is observed experimentally [3] that $D(\omega', q^2)$ is essentially independent of q^2 within the range of the data; i.e.

$$D(\omega', q^2) \approx D(\omega'). \tag{13}$$

The measured [3] values of $D(\omega')$ are given in table 1. Our model agrees with these results. Indeed, keeping ω' fixed and using (2), (11), we find that $D(\omega', q^2)$ is

Table 1
Extracted structure functions from factorization in $F_{2p}(\omega', q^2)$.

Experiment bin	$D(\omega')$	Theory ω'	$D(\omega')$
$8 < \omega' < 12$	0.355 ± 0.0042	10	0.345 ± 0.010
$12 < \omega' < 16$	0.343 ± 0.0054	14	0.342 ± 0.010
$16 < \omega' < 20$	0.335 ± 0.0068	18	0.338 ± 0.001
$20 < \omega' < 24$	0.325 ± 0.0109	22	0.335 ± 0.002
$24 < \omega' < 28$	0.328 ± 0.0151	26	0.332 ± 0.002
$28 < \omega' < 32$	0.321 ± 0.0213	30	0.329 ± 0.001
$32 < \omega' < 36$	0.332 ± 0.0194	34	0.326 ± 0.001
$36 < \omega' < 40$	0.317 ± 0.0265	38	0.324 ± 0.001
$40 < \omega' < 44$	0.320 ± 0.0362	42	0.321 ± 0.001
$44 < \omega' < 48$	0.332 ± 0.0266	46	0.320 ± 0.001

approximately constant in the range of the data[‡3]. Our predictions for $D(\omega')$ are given in the table. The quoted theoretical errors are due to the spread of our results for $D(\omega', q^2)$ at various q^2 and are not infered from the errors in (5). In fig. 2 we give the domain of the $\omega' - q^2$ plane, where our GVD approach anticipates the validity of the factorization (11) – (13) to a 10% accuracy. We remark that this domain is much larger than the one covered by the data [3].

The agreement of our predictions with the experimental results presented above, indicates that our approach calculates correctly the SV induced by the ordinary components of the electromagnetic current at large ω'. It may therefore be used to estimate also the SV due to a new component of the electromagnetic current, such as charm. The effects of charm will appear at higher W; i.e. at higher ω' and (or) q^2. They are indicated by the solid lines in fig. 1, which include the contributions of *all* components of the electromagnetic current. The following points should be made about the charm contribution:

i) The charm contribution reaches scaling very slowly. There are essentially two reasons for this. The *first* and main reason is a pure GVD consequence [9] which demands that scaling for the ordinary and charm currents be established for

$$q^2/m_\rho^2 \gg 1 \quad \text{and} \quad q^2/m_{\varphi_c}^2 \gg 1$$

respectively. The *second* is related to the slow approach to the asymptotic value of $\sigma_D(\varphi_c p, W^2)$. The slower

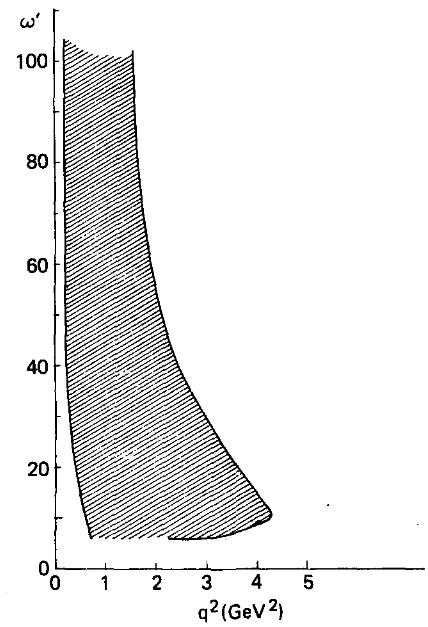

Fig. 2. The shaded region gives the domain where $F_{2p}(\omega', q^2)$ factorizes according to eqs. (11) – (13), to a 10% accuracy.

this cross section reaches asymptoticity, the further the establishment of scaling may be delayed. Our results in fig. 1 indicate that scaling for the charm component should probably be established at $q^2 \sim 70$ GeV^2.

ii) The solid line in fig 1a ($\omega' = 5$) shows an intermediate scaling region for 2 GeV$^2 \lesssim q^2 \lesssim 5$ GeV^2. Using (4) this corresponds to 8 GeV$^2 \lesssim W^2 \lesssim 20$ GeV^2, where $\sigma_D(\varphi_c p, W^2)$ is neglible [17]. Similar results appear also for $\omega' = 10$. Intermediate scaling is a characteristic of moderately large ω', and is due to the fact that the ordinary current contributions reach scaling before charm becomes important. At such ω' there is a range of q^2 above 2 GeV^2, where W^2 is small and $\sigma_D(\varphi_c p, W^2)$ negligible. Keeping ω' fixed and increasing q^2, $\sigma_D(\varphi_c p, W^2)$ becomes eventually appreciable[‡4] and the intermediate scaling is destroyed. The second type of SV is then observed which in turn disappears very slowly. For $q^2 > 70$ GeV^2, a new scaling region takes place where $F_{2p}(\omega')$ is $\sim 45\%$ bigger than its value in the intermediate scaling region. provided that the asymptotic cross section is given by (8a). For a different value of the asymptotic cross

[‡3] More accurately: Within the range of the data and for fixed ω', $D(\omega', q^2)$ is a *very slowly* increasing function of q^2.

[‡4] See eq. (4).

section, we will find in the new scaling region that $F_{2p}(\omega')$ will be

$$\sim 45 \frac{\sigma_D(\varphi_c p)}{(m_\rho^2/m_{\varphi_c}^2)\,\sigma_D(\rho p)} \%$$

bigger than its value in the intermediate scaling region.

iii) At larger ω' $\sigma_D(\varphi_c p, W^2)$ is significant even for very small q^2. In this case the new components of the electromagnetic current become important before the ordinary current contributions reach scaling, and *no* intermediate scaling is seen [20].

iv) For $\omega' \gtrsim 15$ our results are rather insensitive to the detailed form of $\sigma_D(\varphi_c p, W^2)$ in the region (9), (see fig. 1c, d). On the contrary for $\omega' = 5 - 10$ they are sensitive to the detailed form (10) in this region. Region (9) is translated through (4) to the q^2-intervals

$5\ \mathrm{GeV}^2 < q^2 < 40\ \mathrm{GeV}^2$

for $\omega' = 5$, and

$2.3\ \mathrm{GeV}^2 < q^2 < 17\ \mathrm{GeV}^2$

for $\omega' = 10$, where the solid lines in fig. 1a, b have shoulders. The shape of the shoulders is therefore sensitive to the detailed form of $\sigma_D(\varphi_c p, W^2)$ in (9). They will become steeper if the cross section reaches its asymptotic value earlier.

To summarize, we claim in this note that the GVD predictions for the proton structure functions agree with experiment for $\omega' \gtrsim 5$ and any[‡5] q^2. This means that our theory calculates correctly the approach to scaling for the contribution of the ordinary current components, since in the range of the present data the effects of the new currents are negligible. Encouraged by this we also give results for the case of a charm component to the electromagnetic current. Measurements at higher W will reveal the effects of charm which are, (i) an intermediate scaling region for $\omega' = 5 - 10$ which will disappear at higher ω' (ii) a strong SV lasting up to $q^2 \sim 70\ \mathrm{GeV}^2$, and (iii) a final scaling region where $F_{2p}(\omega')$ will be $\sim 45\%$ bigger than its value in the intermediate scaling region if the asymptotic value of $\sigma_D(\varphi_c p)$ is given by (8a).

In the case of a color-octet component to the electromagnetic current, like the one in the Han–Nambu model, we expect qualitatively similar results at large ω'. On the other hand for small ω striking differences may appear. On the basis of PM we expect tha that a color component may contribute strongly there, while the charm current contribution should presumable be suppressed.

Finally we should remark that the above GVD expressions for SV invlove essentially *no* free parameters. Of course they are valid only for large ω. This is to be compared with results of the asymptotically free gauge theories [8, 5], which are presumably valid for any ω, but involve free adjustable parameters. We believe that the combined use of *both* approaches, will provide a deeper understanding of the electroproduction phenomenon, as well as of either one of them.

‡5 Provided of course that W is sufficiently large for the Regge representation to be meaningful.

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