RECENT RESULTS CONCERNING THE ELECTROMAGNETIC STRUCTURE

OF THE NUCLEON* +

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1. Introduction

It has now been five years since the first experimental evidence of scaling was presented at Vienna. Since that time much more has been learned about scaling and the general implications which scaling has for an underlying substructure. In this review, I would like to concentrate on the evidence which exists for and against the parton and the light-cone ideas.

The single arm electroproduction experiments at SLAC have much to say about light cone ideas. Statements which are testable in electroproduction and which seem to be firm predictions of light cone and parton theories nowadays are:

- a) vW_2 must scale (1)
- b) $4 > vW_2^n / vW_2^p > 0.25^{(2)}$ c) $R = r(r) (r)^{(3)}$

$$\mathbf{r} = \mathbf{r}(\omega) / \mathbf{v}^{\prime}$$

1. A.

where ω is a scaling variable.

In order to examine these questions, a number of experiments have been done since 1968, and more are continuing. I have combined the results of many of the completed SLAC experiments to examine points a) and b); point c) will be treated using results from the recent MIT thesis of E. Riordan. (4) A number of excellent experiments have been performed at DESY during this time. However, given the subject of this talk, the kinematical region of the DESY data is limited, and so I have not included any of these data.

2. Kinematics and Some Definitions:

The general kinematics of $e(\mu) \ N \rightarrow e(\mu) + X$ is as follows⁽⁵⁾; one photon exchange dominance is assumed throughout. For this paper $m_{\ell} = m_{e}$.



conventionally we define

$$Q^{2} = -q^{2} = -(\ell - \ell')^{2} = 2 \frac{2}{m_{\ell}} + 2(E E' - |\vec{p}| \cdot |\vec{p}| \cos \theta)$$
(1)
= $Q^{2} \min + 4 |\vec{p}| \cdot |\vec{p}| \sin^{2} \theta/2 > 0$

$$v = \frac{P \cdot q}{M} = E - E', M = mass of nucleon.$$
 (2)
(proton or neutron)

$$s = W^2 = 2 Mv + M^2 - Q^2$$
. (3)

$$K = (s - M^2)/2M.$$
(4)

Note that Q^2 , v, s, K are Lorentz invairants and (E, \vec{p}), (E', \vec{p} ') are the incoming and scattered lepton energy and momentum in the laboratory frame in which θ is the laboratory scattering angle of the lepton.

The double differential cross section for lepton detection is commonly expressed as ,

$$\frac{d^2\sigma}{d\Omega dE^*} = \sigma_{MOTT} \left[W_2(s, Q^2) + 2 \tan^2 \theta / 2 W_1(s, Q^2) \right]$$
(5)

 \mathbf{or}

$$= \Gamma_{t} \sigma_{t} (s, Q^{2}) \left[1 + (\epsilon + \delta) R (s, Q^{2}) \right]$$
(6)

where

$$\sigma_{\text{MOTT}} = \frac{4\alpha^2 E^{*2} \cos^2 \theta/2}{q^4}$$
(7)

$$\Gamma_{t} = \alpha/4\pi^{2} \frac{W^{2} - M^{2}}{MQ^{2}} \frac{E^{*}}{E(1-\epsilon)}$$
(8)

$$\epsilon = \frac{1}{1 + \frac{2(q^2 + v^2) \tan^2 \theta/2}{q^2(1 - q^2 \min / q^2)^2}}$$
(9)

$$\delta = \frac{2\pi_{\ell}^2}{\sigma^2} (1-\epsilon)$$
(10)

In the kinematical region I shall discuss Q_{\min}^2 and δ are nigligible for electrons. In most of the following, $W_2(s, Q^2)$ and $R(s, Q^2)$ will be used to describe the data.

One can easily show that,

$$W_1 = \frac{4\pi^2 \alpha}{K} \sigma_T, \qquad W_2 = \frac{4\pi^2 \alpha}{K} \frac{Q^2}{Q^2 + v^2} \sigma_T^{(1+R)}$$
 (11)

The conventional use of $W_2(s, Q^2)$ and $R(s, Q^2)$ to describe the data becomes clearer when one examines the phenomenon of scaling.

If scaling is true for the structure functions of the nucleon for finite values of Q^2 , s, then,

$$vW_2(s, q^2) = F(\omega_F).$$
 (12)

 $\omega_{\rm F}$ is some scaling variable which has the property that in the B.J. limit⁽¹⁾ of Q², $\nu \rightarrow \infty$, it becomes equal to the first proposed scaling variable, $\omega_{\rm F} \rightarrow 2M\nu/Q^2$.

Some common scaling variables which support varying points of view about the "meaning" of scaling are, (with common notations),

$$\omega = 2Mv/q^{2} = 1/x = 1/\xi^{(1)}$$

$$\omega^{i} = 1 + s/q^{2} = \omega + M^{2}/q^{2} = 1/x^{i}^{(6)}$$

$$\omega_{W} = \frac{a+s}{b+q^{2}}^{(7)} \quad a \sim 0.6, b \sim 0.42$$
(13)

The references will just get the reader started if he is interested in the "meaning" of scaling as now there are over 500 theoretical⁽⁸⁾ papers on the subject.

If $R(s, Q^2) \ge 0$ in the B.J. limit, then from (ll), $W_1(s,Q^2)$ scales if $\gamma W_2(s, Q^2)$ does (in the B.J. limit). This point is of some interest. How $R(s, Q^2)$ approaches zero (if it does) in the B.J. limit is of crucial interest to light cone theories which in general expect⁽³⁾

 $R(s,Q^2) \rightarrow r(\omega)/\nu \tag{14}$

3. Recent Experiments in Electroproduction:

As I mentioned in the introduction, I have combined the results of a number of SLAC electroproduction experiments to test scaling and examine the neutron/proton ratio. I would like to briefly describe these experiments and how I used them. I will assign a systematic error to each experiment as I discuss it. These should be taken as rough estimates, as one number does not generally describe the systematics. For a more complete description of the systematic errors, I refer the reader to the primary source material (when available). The systematic error for the ratio of deuterium to hydrogen is estimated to be half that for hydrogen alone. I will show typical data from each experiment starting from the smallest angle in order of increasing angle.

Figure 1 shows a hydrogen spectrum of an experiment done by Group-A at SLAC⁽⁹⁾. It is a 4° experiment using both H_2 and D_2 as targets. W goes to 5.5 GeV, and Q^2 goes to 1.8 $(\text{GeV/c})^2$. Systematic errors on hydrogen

are $\sim \pm 4\%$. There are excellent resonance data in the experiment, and also data at large ω and $Q^2 \gtrsim 1(\text{GeV/c})^2$ to determine n/p ratios there with smaller errors than the other experiments.

Figure 2 shows a deuterium spectrum from an experiment of the MIT-SLAC collaboration at 6° and 10°.^(10,11) Data were taken on both hydrogen and deuterium. The resonances are not seen in the data shown because of the limited statistics and the deuteron Fermi motion effects. The experiment does have reasonable resonance data in hydrogen up to $q^2 \sim 6(\text{GeV/c})^2$. Again W goes to 5.5 GeV; the 6° data have q^2 to 3.6(GeV/c)², and the 10° data have q^2 to 8.5(GeV/c)². The systematics of this experiment are ~ ± 6%. These are the data for which n/p was first extracted, ⁽¹¹⁾ and they were used with larger angle data to extract R(s, q^2)⁽⁴⁾.

Figure 3 shows a hydrogen spectrum from a SLAC-MIT experiment using only H₂ as target. Data were taken at 18°, 26°, 34°.⁽⁶⁾ The experiment was performed in 1968. W extends to 5.25 GeV and Q^2 to $20(\text{GeV/c})^2$. Little resonance information exists in these data due to the very rapid decrease of cross sections with decreasing W at the high Q^2 measured. The systematic errors of this experiment are ~ $\pm 6\%$. With these data the first "real" tests of scaling were done, and they were used in the first R separation leading to $\ddot{R} = 0.18 \pm 0.1.^{(6)}$

Figure 4 shows an MIT measurement done in collaboration with the SLAC Spectrometer Facilities Group over essentially the same kinematic range as the previously described experiment at 18° , 26° , 34° .^(4,12,13) Better statistical precision was obtained, and deuterium was measured for the first time at large angles. These data were used in n/p studies near $\omega = 1$,⁽¹²⁾ and in conjunction with the 6° , 10° data previously described, R for hydrogen

and deuterium was obtained. The systematic errors in this experiment are~ + 6%.

Data from the experiments described above with $W \leq 4.9$ GeV (a conservative cut based mainly on considerations of radiative corrections), and $Q^2 > 0.4 (\text{GeV/c})^2$ were combined into a grid of Q^2 ,s as shown in Figure 5. The grid obtained $vW_2(s, Q^2)$ under various assumptions for R consistent with existing information⁽⁴⁾ as will be discussed later. The procedure used to construct the grid was model insensitive, and it propagated the statistical errors of the data correctly. In the resonance region, W < 1.9 GeV, data were combined into bins of $\Delta W = 50$ MeV, and for W > 1.9 GeV, the bins were $\Delta W = 250$ MeV. In Q^2 the bin width varied as indicated in Figure 5 by the dashed lines. For reference, $\omega^* = 3,5$ lines are shown in the figure, and the elastic scattering obtained separately⁽¹⁴⁾ is kinematically represented.

4. Discussion of $R(s, q^2)$:

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In the list in the introduction I had questions concerning $R(s, q^2)$ listed last, c). But, in order to examine scaling and the n/p ratio properly, we should have some idea of what vW_2 and W_1 , or equivalently vW_2 and R, are separately. So I will discuss point c) first relying heavily on information from Reference 4.

Figure 6 shows the region where $R(s, Q^2)$ was determined. Riordan has made a grid of R in Q^2 , s of about 110 points. In Table I are shown a number of fits he made in that grid. I'll talk later about some of the fits that are of particular interest. First consider the general kinematical dependence of R_p . Figure 7a shows R_p averaged over W from 2 to 4 GeV plotted as a function of Q^2 . In Figure 7b is shown R_p averaged over v between 3 to 12 GeV plotted as a function of ω . Only the statistical errors are shown. As for the systematic effects, one should note that a 1%

shift in the 6° and 10° data relative to the large angle data gives a 20% shift in R_p , and a few percent systematic difference between experiments is very likely. One sees in 7a that at Q^2 near zero R_p is consistent with falling toward zero as it must. There may be an increase in R_p initially as Q^2 increases, with a subsequent drop off. In 7b perhaps there is a slight increase in R_p as ω increases. Of course the systematics could play an important part in these trends if they were included.

Now to the fits of Table I. One must realize again that the errors quoted are statistical only, and the systematic effects have not been included.

Fit 1, assuming a constant value for R, allows a comparison with the previous measurements of R in the deep inelastic region.⁽⁶⁾ As mentioned previously the older experiments obtained $\bar{R} = 0.18 \pm 0.1$, where the error includes the effects of estimated systematic errors. Chi-square per degree of freedom indicates that this fit is still acceptable with $\bar{R} = 0.168 \pm 0.014$ (statistical error only).

Fit 2, $R = a Q^2$, has a large chi-squre per degree of freedom compared to a number of the other fits. The poor fit probably excludes this form in the present range of data.

Fit 4, $R = a Q^2/v^2$, is a poor representation of the data. This form was suggested by the naive quark model (spin $\frac{1}{2}$ constitutents with a definite light mass). Again the poor fit probably excludes this form in the present range of data.

Fit 6 is of the form suggest by light cone algebra.⁽³⁾ This becomes more obvious when the a and b coefficients are set to zero (they are consistent with zero). Then,

$$R = (0.09 \pm 0.01) Q^2 / v^2 x^2 = 2 M(0.09 \pm 0.01) \omega / v$$

$$= r(\omega) / v, \quad r(\omega) = (0.09 \pm 0.01) 2M \omega.$$
(15)

The chi-square per degree of freedom for this fit is slightly smaller than for Fit 1, a constant.

To further study the question of the scaling of vR, Riordan has plotted vR vs v for various values of ω . As Figure 8 indicates (this is a subset of the data presented in Reference 4), vR_p indeed scales within the errors of the experiment. So the light cone hypothesis is consistent with the data, considering the statistical errors shown, but the data are not very constraining.

Information on R_d of the deuteron is needed to examine n/p with confidence. The MIT people have measured the difference between R_d and R_p in a quite sensitive way and found that $R_d = R_p$ within errors. A combined version of the results is shown in Figure 9.

5. n/p from the Combined Data:

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Since the determination of $\sigma_d^{\prime}/\sigma_p^{\prime}$ is a ratio measurement, higher accuracy can be obtained for σ_d / σ_p than for σ_d or σ_p separately. This is because in a ratio measurement many sources of errors, e.g., solid angle uncertainties, radiative corrections, tend to cancel in the cross section ratio. Hence the estimate of systematics in the ratio σ_d/σ_p is one-half that of σ_p alone. In Figure 10 is plotted (σ_n/σ_p) vs x' using combined data from three of the four experiments I have mentioned, those experiments which have both hydrogen and deuterium data. The systematic effects introduce an uncertainty of typically + 0.05 in (n/p). One should note that the deuterium nuclear physics corrections are less than 2% for x' lower than 0.65. However, if one moves to $x^{\dagger} = 0.85$, where σ_{n}/σ_{n} is approximately one-third, nuclear corrections are about 11% for σ_d/σ_p , or about 40% for (σ_n/σ_p) . The principal correction arises from Fermi motion.⁽¹⁵⁾ In Figure 10 it is evident that $vW_2^n \neq vW_2^p$ over the entire kinematic range shown. Also, as the dashed line highlights, the quark model lower bound of $0.25^{(2)}$ is not threatened by the data at this time.

Figure 11 shows the small x' region, i.e., the large ω ' region for ω ' between 5 and 25. These are 4° data with $Q^2 > 0.87$.⁽⁹⁾ At ω ' = 15, Q^2 is 1, and I think one can say with confidence that σ_n is not equal to σ_p .

Figure 12 shows $vW_2^p - vW_2^n$ assuming $R_p = R_n = 0.168$ vs x' for $Q^2 > 0.9(\text{GeV/c})^2$, W > 1.8 GeV. Immediately evident in the data using this representation vs x' is a "peak" at x' ~ 0.3. A naive interpretation of this result in terms of lightly bound quarks would suggest a quasi elastic scatterng peak from constituents with an effective mass of about 300 MeV. Of course, the curve must equal zero at x' = 1, and presumably will be zero at x' = 0, so we may be observing a lump, not a peak.

Now I would like to discuss the following sum rule for n-p,

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$$\int_{1}^{\infty} \frac{d\omega}{\omega} \left[v W_2^{p}(\omega) - v W_2^{n}(\omega) \right] = 0.33$$
(16)

In experimentally evaluating (16) the limit $\omega \to \infty$ or $s \to \infty$ is important. (16) can easily be derived using a parton model assuming that the infinite sea of $q\bar{q}^{\nu}$ pairs acts the same in the presence of proton or neutron valance quarks.⁽¹⁶⁾ Recently, it has been pointed out that the sum rule may be obtained by assuming exact exchange degeneracy for t-channel meson exchanges in hadronic reactions.⁽¹⁷⁾ We know that exchange degeneracy is good to perhaps $\pm 20\%$ in the t-channel for hadronic reactions, so a more realistic derivation⁽¹⁷⁾ of (16) might expect it to be satisfied to $\pm 20\%$, i.e.,

$$\int_{1}^{\infty} \frac{d\omega}{\omega} \left[F_{2}^{p}(\omega) - F_{2}^{n}(\omega) \right] = 0.33 + 0.07$$
(17)

The first experimental evaluation of the sum rule was reported at Kiev in $1970^{(11)}$. At that time data for n/p existed to $\omega = 12$ and,

$$\int_{1}^{12} \frac{d\omega}{\omega} \left[v W_2^p(\omega) - v W_2^n(\omega) \right] = 0.13 \pm 0.04, \qquad (18)$$

where the error was an attempt to estimate mainly systematic effects. In order to get an estimate of the high energy contribution $(\omega \rightarrow \infty)$, normal Regge exchanges were assumed to dominate the high energy behavior $(R_p = R_n \leq 0.18 \text{ was also assumed})$. Then $vW_p^p - vW_p^n \sim 0.03 (12/\omega)^{\alpha}$, $\omega > 12$. (19)

This led to the extrapolated result,

$$\int_{1}^{\infty} \frac{d\omega}{\omega} \left[\nu W_2^{p}(\omega) - \nu W_2^{n}(\omega) \right] = 0.19 \pm (?)$$
taking $\alpha = \frac{1}{2}$. (20)

This result was difficult to reconcile with the theoretical result above. We are now able to use data from $\omega = 5$ to 20 of greater accuracy and precision than available at Kiev, as well as extending above $\omega = 12$. Figure 11 shows this data. We now obtain,

$$\int_{1}^{20} \frac{d\omega}{\omega} \left[v W_2^p(\omega) - v W_2^n(\omega) \right] = 0.18 \pm 0.04, \qquad (21)$$

where again the error is an attempt to estimate mainly systematic effects. So, the present experimental evaluation of the sum rule to $\omega = 20$ is essentially as large as the value obtained by extrapolating to $\omega = \infty$ in 1970 (Equation (20)). If one now makes the same mistake again and extrapolates from $\omega = 20$ to ∞ using Regge, we obtain,

$$\int_{1}^{\infty} \frac{d\omega}{\omega} \left[\nu W_2^{p}(\omega) - \nu W_2^{n}(\omega) \right] = 0.28 \pm (2)$$
(22)

which is probably wrong, but illustrates a point; that clearly the immediate threat posed by (20) to the theory has been removed for the present. The unmeasured high energy behavior of $vW_2^p - vW_2^n$ contributes importantly to the sum rule and data with $\omega > 20$, $Q^2 > 1$ (GeV/c)² are certainly crucial

in proving the validity of Equation (17).

6. Scaling for the Proton

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In past conferences scaling was demonstrated by plotting limited amounts of data interpolated to fixed ω or ω ' versus q^2 or ν , or by showing all data with W > 1.8, $q^2 > 1(\text{GeV/c})^2$ on so-called Gee-Whiz plots.



The data are getting considerably better now, covering a greater kinematic range (see figure 5), so that they can be presented in a more quantitative fashion to test the ideas of scaling.

What follows is an attempt to do this by looking at moment integrals of vW_2 at fixed Q^2 . I define, $\omega'=5$ $B_n(Q^2) \equiv \int (d\omega'/\omega'^{2n+2}) vW_2^p(\omega', Q^2)$ (23) elastic peak

$$4q^{2} = \int_{\substack{\text{elastic}\\\text{peak}}} \left(\frac{ds}{q^{2}} / (1+s/q^{2})^{2n+2}\right) v W_{2}^{p}(s, q^{2}), \qquad (23)$$

With n = -1/2, 0, 1/2, ... 3. Also I take R = 0.168, but the integrals are insensitive to R, as I shall discuss. The Q^2 -s grid of Figure 5 was used in the evaluation of the integrals. When data were not available, e.g., at high s, high Q^2 , I used a scaling fit in ω' ,

$$F(\omega^{*}) = \sum_{m=3}^{T} C_{m} (1-1/\omega^{*})^{m}$$
(24)

where the C_m were determined from the data of the grid. Thus for high Q^2 some fraction of the integrals automatically scales. Table II has the values of some of the moments and the approximate fraction of the integral which is evaluated using the scaling fit vs data of the grid.

Now to discuss some points of difficulty. The definition of $B_n(Q^2)$ is usually a B.J. limit definition.⁽¹⁸⁾ Hence the evaluation of the integrals at the finite Q^2 , s available is not simple to interpret. I have chosen ω' as the relevant scaling variable for two reasons. First, I have a prejudice that ω' incorporates the resonances in a reasonable way.⁽¹⁹⁾ Second, a large amount of data at lower Q^2 is resonance data, and if those data are left cut, then what one can say about the data-determined values of $B_n(Q^2)$, and hence scaling, is diminished considerably. In any case, given the moments in ω' one can obtain them for any other reasonable scaling variable by a Taylor expansion to that variable.

The moments have many useful possibilities for interpretation. I'll now give some examples of how the moments can be used.

a) Suppose that as Q² → ∞, B_n(Q²) = C_n, all n. This would imply exact scaling. Maybe in ω¹, Q² is finite when scaling begins.
b) Another possibility is that expressed by Chanowitz and Drell⁽²⁰⁾ of a scale breaking due to the vector gluon interaction, a parton form

factor. In this case,

$$B_n(Q^2) \sim (1 + Q^2/\Lambda^2)^{-2}$$
 as $Q^2 \to \infty$ for all n. (25)

c) A third possibility is that first suggested by K. Wilson⁽²¹⁾, anomolous dimensions, which is also a scale breaking phenomonon. In this case,

$$B_{n}(Q^{2}) \sim (1/Q^{2})^{\epsilon_{n}}$$

$$Q_{2} \rightarrow \infty$$
(26)

with $\epsilon_0 = 0$, $\epsilon_{n+1} > \epsilon_n \geq 0$, n = 1,2,...

The ϵ_n are the anomolous dimensions of the operators in a Wilson operator expansion. If anomolous dimensions exist, $B_0(Q^2)$ should be constant as a function of Q^2 while $B_1(Q^2)$, $B_2(Q^2)$,... should decrease more and more rapidly as n increases for increasing Q^2 .

In figures 13a-h are shown the moments evaluated as described above vs q^2 . The error flags are estimates of one standard deviation <u>systematic</u> errors. These were obtained by a Monte Carlo technique using the systematic errors of the individual experiments given earlier in this talk. These errors should be taken as guides and not be used in a purely statistical fashion. The purely statistical errors in the $B_n(q^2)$ are small since a large amount of data is being integrated over. 5% is shown on each graph for reference. Note that some graphs have suppressed zeros. Again, one should refer to Table II to determine what fraction of the integral comes from data and what fraction from the scaling fit (24).

It appears that the lowest two moments $B_{\frac{1}{2}}(Q^2)$, $B_0(Q^2)$ don't have a Q^2 dependence above $Q^2 = 1.5(\text{GeV/c})^2$ within errors. Civen the values in Table II a Λ of ≤ 12 GeV seems safely excluded for the Chanovitz-Drell parton form factor. This corresponds to a parton size of $\leq 1.7 \times 10^{-2} \text{fm}$.

As n increases the $B_n(Q^2)$ appear to develop a progressively stronger Q^2 dependence, until a quite obvious drop-off is apparent in $B_3(Q^2)$, Fig. 13h. For reference the elastic contribution is shown for $B_2(Q^2)$, $B_3(Q^2)$ in Figures 13f, 13h. It is clear that the elastic contribution, and so the resonance contribution, is becoming appreciable at medium Q^2 as n approaches 3. One should expect this since large n means higher powers of $1/\omega^4$ in the integrals. This weights the low ω^4 , or resonance region more heavily.

Might the Q^2 dependence be an R(s, Q^2) effect? In Table I five of the fits Riordan made have a chi-square per degree of freedom less than 1. These fits are labeled by R_1-R_4 , R = 0.168 is the fifth. As mentioned previously, the moments shown were evaluated for R = 0.168. In Figures 14a, b are shown the two extreme moments $B_{-\frac{1}{2}}(Q^2)$ and $B_3(Q^2)$ evaluated for R_i , i=1,...,4 and then divided by the moment integral evaluated with R = 0.168. The worst case of an R dependence is that of $B_3(Q^2)$ yielding a 6 or 7 percent deviation in the moment, which enhances the Q^2 dependence. So the Q^2 dependence doesn't appear to be an R effect. Why then is there a Q^2 -dependence in the higher moments Possible reasons might be:

a) It doesn't make sense to include predominantly resonance contributions in evaluating the moments. We need higher Q^2 data over a range where the resonances are negligible in the moments evaluated. If this is done the Q^2 dependence may go away.

b) Use the magic scaling variable $\tilde{\omega}_{m}$ and all moments will be flat in ϱ^{2} .

c) The resonances are important for the higher moments and resonance data are almost non existent for large $Q^{2(22)}$.

d) It is easy to fit the $B_n(Q^2)$ to the form $(1/Q^2)^{\epsilon_n}$, for $Q^2 > 1.5(\text{GeV/c})^2 \epsilon_3 \sim 0.14$, $\epsilon_{5/2} \sim 0.10$, $\epsilon_2 \sim 0.08$, $\epsilon_{3/2} \sim 0.06$, $\epsilon_1 \sim 0.04$, $\epsilon_1 \sim 0.02$, $\epsilon_0 \sim 0$.

Hence the Q^2 dependence in the $B_n(Q^2)$ is consistent with the hypothesis of anomalous dimensions.

I regard possibilities a) - d) with decreasing probability. In any event the $B_n(Q^2)$ are numbers based more or less solidly on experiment which may now be pondered by the theorists.

6. Tests of Substructure from Neutrinos:

Figure 15 shows results of a Cal. Tech. neutrino experiment at N.A.L.⁽²³⁾ The figure shows $d\sigma^{VFe}/dx vs x$ which under certain assumptions (see talk of Franzinetti in these Proceedings) can be related to $vW_2^d(\omega)$ from electron-deuteron scattering. The normalization is arbitrary. The shape obtained from neutrinos from pion decay (< $E_V > = 50$ GeV) is compared with the electroproduction results and generally agrees.

In Figure $16 < Q^2 > vs$ the incident neutrino energy is plotted (again the Cal. Tech. experiment). In this case kaon neutrino data ($< E_V > = 145$ GeV) are also included. These neutrino results yield a limit for the A parameter of Chanowitz and Drell of 5 GeV/c². This limit is presently somewhat poorer than the electron limit, but the experimenters hope that in the near future they will have a lot more data to press this number considerably. A in this case can be a parton size as in the case of electroproduction, but can also indicate a breakdown of the weak interaction via an intermediate vector boson.

Is there further evidence for substructure?

a) Inelastic Compton Scattering

Two very difficult experiments have been done. One of them⁽²⁴⁾ observing

 $\gamma + p \rightarrow \mu^+ \mu^- + X$ and the other⁽²⁵⁾

 $\gamma + p \rightarrow \gamma + X$

The kinematics of the reaction is as follows:



According to Bjorken and Paschos⁽¹⁶⁾ the cross section can be expressed as:

$$\left(\frac{d^{2}\sigma}{d\Omega dE'}\right)_{\gamma P} = \frac{v^{2}}{EE'} \frac{\langle \Sigma Q_{i}^{\mu} \rangle}{\langle \Sigma Q_{i}^{2} \rangle} \left(\frac{d^{2}\sigma}{d\Omega dE'}\right)_{ep}$$
(27)

where Q_i are the charges of the partons. It seems to me that we should only expect qualitative agreement with this theory, as in the ep-inelastic case experiment is a factor of two smaller than the theoretical prediction.⁽¹⁶⁾

The Cornell group has published⁽²⁴⁾ their μ -pair experiment, and they see a large excess of $\mu^+\mu^-$ at large P₁ which is 20 times bigger than the Bjorken-Faschos prediction.

The results of another experiment were submitted to the conference (25). Figure 20 shows results of this Santa Barbara experiment done at SLAC. In this experiment the π° yields were measured in the same apparatus as the single γ yields. The experimenters did a subtraction of the π° yield based on the measured 2 γ coincidence rate which was derived using a Monte-Carlo calculation.

The experiment was done with a bremsstrahlung spectrum. Plotted is the cross section against the apparent E^{\dagger} of the photon. A subtraction has been done, leading to the results of Figure 21, the 1 γ -excess cross section. The solid lines are the measurements, the dashed line the Bjorken-Paschos prediction with

 $<\Sigma Q_{i}^{\mu} > / <\Sigma Q_{i}^{2} > = 1$

(28)

For quarks this value is 0.407; in that case the theoretical curve drops by an additional factor of 2.5. The results are again larger than the Bjorken-Paschos prediction by a factor of 6 or so.

b) Another source of substructure information is a CERN, Columbia, Rockefeller ISR experiment⁽²⁶⁾

p + p -> e⁺ + e⁻ + X

This was done at $s = 2850 \text{ GeV}^2$.

Figure 22 shows $d\sigma/dm_{e^+e^-}$ versus the mass of the e^+e^- pair. Curve 3 gives an experimental upper limit with a 95% confidence level, curve 1 is the theory of Brell-Yan,⁽²⁷⁾ which predicts

$$d\sigma/dm_e^+e^- \sim F\left(\frac{s}{m_e^2+e^-}\right)$$
(29)

and curve 2 gives an estimate of the lepton pair production with a 2γ intermediate state.

It of course is extremely interesting to see if more than an upper limit can be measured and to see if the cross sections are actually scaling.

7. Conclusions

Within the context of this paper I believe I have shown that the parton and light cone ideas discussed in the introduction are consistent with the data.

a) Using the moments $B_n(Q^2)$, the data seem consistent with scaling given the uncertainties associated with being at limited Q^2 and s. However, the apparent Q^2 dependence of $B_n(Q^2)$ for $n \sim 3$ indicates a consistency with the ideas of anomolous dimensions also. The resolution of this important point awaits larger Q^2 and s data.

b) As Figure 10 indicates, the absolute lower bound for vW_2^n/vW_2^p of 0.25 is not threatened by the data at this time.

c) The new experiments measuring $R^{(4)}$ are certainly consistent with the requirement that $R = r(\omega)/\nu$; however, greater accuracy is needed before a constraining test of light cone ideas is to be made. d) Experiments other than inelastic electron measurements have much to say about substructure. Neutrino experiments, though statistically limited, show suprising consistency with the electron data. Also other large P₁ processes show promise for future tests.

8. Acknowledgements:

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Table I - Global Fits to Rp

(From Reference 4.) Only statistical errors are indicated. Fits # 1,5,6,8,9 used in scaling study.

#	Parametrization	Best-fit Coefficients	$\frac{x^2/n_d}{x}$
1	$R_p = \alpha$	$a = 0.168 \pm 0.014$	0.81
2	$R_p = aQ^2$	$a = 0.027 \pm 0.003$	1.51
3	$R_{p} = \alpha Q^{2}(1-x)$	$a = 0.052 \pm 0.006$	1.30
4	$R_p = \alpha Q^2 / v^2$	$a = 1.009 \pm 0.108$	1.39
5	$R_{p} = f(x)Q^{2}/v^{2}$	a -= 7.85 + 1.71	0.80
	$f(x) = a+b(1-x)+c(1-x)^2$	$b = -30.85 \pm 6.10$	
		$c = 31.49 \pm 5.32$	
6	$R_p = f(x)Q^2/v^2$	$a = 0.030 \pm 0.258$	0.76
	$f(x) = \alpha/(1-x)+b+c/x^2$	$b = 0.229 \pm 0.540$	
		$c = 0.087 \pm 0.012$	
7	$R_p = \alpha(1 + Q^2/v^2) - 1$	$a = 1.048 \pm 0.013$	1.27
8	$R_p = g(x) (1+Q^2/v^2) - 1$	$a = 1.27 \pm 0.20$	0.58
	$g(x) = a+b(1-x)+c(1-x)^2$	$b = -1.52 \pm 0.63$	
-		$c = 1.70 \pm 0.48$	
9	$R_p = g(x) (1+Q^2/v^2) - 1$	$a = 0.784 \pm 0.038$	0,59
	$g(x) = a + b/x + c/x^2$	$b = 0.087 \pm 0.014$	
		$c = -0.0035 \pm 0.0009$	

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TABLE II

Contributions from the scaling fit (Equation (15)) to the moments evaluated to $\omega' = 5$, and $\omega' = 2.22$. Table is for upper limit of integrals at $\omega' = 5$.

Moment	Q ² (GeV/c) ²	Value	Scaling Fit Contributio Value	n
B_	16	0.087	0.86	-
B	13	0.087	0.74	
В	11	0.087	0.47	
Bo	9	0.087	0.23	
Bo	7	0.087	0.14	
Bl	16	0.0139	0.66	
B	13	0.0138	0.47	
Bl	11	0.0139	0.22	
B ₁	9	0.0139	0.08	
B ₂	16	0.00338	0.12	
B ₂	13	0.00336	0.23	
B ₂	11	0.00343	0.08	
B ₃	16	0.00114	0.24	
B ₃	13	0.00114	0.09	

Note that evaluating the moment integrals to $\omega' = 2.22$, the limit of data at $q^2 = 13(\text{GeV/c})^2$, does not charge the slopes in q^2 of the $B_n(q^2)$ shown in Figures 13a-h significantly. It just changes the overall normalization. For this limit of $\omega' = 2.22$, the $B_n(q^2)$ are obtained from essentially only data, the scaling fit playing a minor role.

FIGURE CAPTIONS

- Figure 1. Hydrogen spectrum at 4° , E = 16 GeV, from reference 9.
- Figure 2. Deuterium spectrum at 6° , E = 19.5 GeV, from reference 10.
- Figure 3. Hydrogen spectrum at 26° , E = 15 GeV, from reference 6.

Figure 4. Hydrogen spectrum at 26° , E = 15 GeV, from reference 4, 12, 13.

- Figure 5. Q^2 -s grid showing the location of combined data. The dashed lines indicate the Q^2 bins. Lines for $\omega'=3,5$ are shown for reference.
- Figure 6. The separation region in the $s-Q^2$ plane where R was obtained. Data at three or more angles are available to determine R in shaded region. From reference 4.
- Figure 7a. R_p averaged over 2.0 $\leq W \leq 4.0$ plotted vs. Q^2 . Errors shown are purely statistical. From reference 4.
- Figure 7b. R averaged over $3.0 \le \nu \le 12.0$ plotted vs. ω . Errors shown are purely statistical. From reference 4.
- Figure 8. νR_p vs. ν for fixed ω . This is a subset of the data presented in reference 4. Errors are purely statistical.
- Figure 9a. $\Delta = R_d R_p$ averaged over 2.0 $\leq W \leq 4$ plotted vs. Q^2 . Errors shown are purely statistical. From reference 4.
- Figure 9b. $\Delta = R_d R_p$ averaged over $3 \le \nu \le 12.0$ plotted vs. ω . Errors shown are purely statistical. From reference 4.
- Figure 10. (n/p) for the combined data plotted vs. x'. $R_p = R_n$ is assumed. $Q^2 > 0.9(GeV/c)^2$ and W > 1.3 GeV. The data have a kinematic range shown in Figure 5, and a binning as described in section 3.
- Figure 11. (σ_n / σ_p) vs. ω° for $Q^2 > 0.87$ from the 4° experiment reference 9. The indicated estimate of systematic error was a large contribution to the estimated error in equation 21.

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 $vW_2^{P} - vW_2^{n}$ vs. x' under the assumption that $R_n = R_n < 0.168$. Figure 12. The data presented is for $Q^2 > 0.9(GeV/c)^2$ and W > 1.8 GeV. Note that as $x' \rightarrow 1$, $Q^2 \rightarrow \infty$ and as $x' \rightarrow 0$, $s \rightarrow \infty$. $\underline{B_1}(Q^2)$ vs. Q^2 for $R_p = 0.168$. Figure 13a. Figure 13b. $B_{p}(Q^{2})$ vs. Q^{2} for $R_{p} = 0.168$. $B_{\frac{1}{2}}(Q^2)$ vs. Q^2 for $R_p = 0.168$. Figure 13c. $B_1(Q^2)$ vs. Q^2 for $R_n = 0.168$. Figure 13d. $B_{2/2}(Q^2)$ vs. Q^2 for $R_p = 0.168$. Figure 13e. $B_{p}(Q^{2})$ vs Q^{2} for $R_{p} = 0.168$, shown with crosses is the Figure 13f. contribution of elastic scattering. $B_{5/2}(Q^2)$ vs Q^2 for $R_p = 0.168$. Figure 13g. $B_2(Q^2)$ vs. Q^2 for $R_0 = 0.168$, shown with crosses is the Figure 13h. contribution of elastic scattering. Figure 14a, b. The R dependence of the moments vs Q^2 . Shown are $B_n^{Ri}(Q^2)/$ $B_{-}^{R=0.168}(q^2)$ for R_i , i = 1, 2, 3, 4 of table I. In the evaluation of $B_n^{Ri}(Q^2)$, the Q^2 -s grid described in section 3 was recalculated assuming $R_p = R_i$. Only the extreme moments $B_{1}(Q^2)$ and $B_{3}(Q^2)$ are shown. The other moments have an interpolating R dependence. $d\sigma^{VFe}/dx$ (arbitrary units) vs. x'. The graph shows π neutrinos Figure 15. $(<E_{y}> = 50 \text{ GeV})$ only. Overplotted is $F_{2}^{ed}(x)$. From reference 23. Mean Q^2 , $\langle Q^2 \rangle$ vs. incident neutrino energy for pion neutrino Figure 16. (<E_y> = 50 GeV), and kaon neutrino (< E_y> = 145 GeV) events. Overplotted is $\frac{d^2 \sigma^{VFe}}{dxdv} = G^2 ME_v / \pi F_2(x) / (1+Q^2/\Lambda^2)^2$. For $\Lambda = 0$ and $\Lambda = 5 \text{ GeV/c}^2$. From reference 23.

- Figure 17. Single γ cross section, $d^2\sigma/dE^{\dagger}d\Omega$ vs. apparent E^{\cdot}. Apparent E^{\cdot} is the energy observed deposited in the lead glass counters, (apparent E^{\cdot}) \leq E^{\cdot}. The data are plotted for various apparent P₁ = (Apparent E^{\cdot}) sin θ .
- Figure 18. Parameterized 1γ excess cross section vs E' for various $P_{\perp} = E^{*} \sin \theta$. Also shown is the prediction of Bjorken-Paschos with $\langle \Sigma Q_{i}^{4} \rangle / \langle \Sigma Q_{i}^{2} \rangle = 1$. For the Quark model $\langle \Sigma Q_{i}^{4} \rangle / \langle \Sigma Q_{i}^{2} \rangle = 0.407$. A monte carlo is used to obtain E' from (apparent E') as well as being used in the extraction of the parameterized 1γ excess cross section. From reference 25.
- Figure 19. dσ/dm_e+_e- vs. m_e+_e- for an s of 2850 GeV². Curve 1 is the scaling model of Drell-Yan, curve 2 is an estimate of e⁺e⁻ production with a 2γ intermediate state and curve 3 is a 95% C.L. experimental upper limit to the e⁺e⁻ cross section.





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