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STRUCTURE FUNCTIONS AND THE EMC EFFECT
- WHERE ARE WE NOW AND WHERE ARE WE GOING TO? -

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STRUCTURE FUNCTIONS AND THE EMC EFFECT

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INTRODUCTION

This review is concerned with recent experimental advances in the study of deep inelastic scattering and the study of the nucleon structure functions. I shall concentrate on the data concerning the "EMC Effect" and will only comment on the status of conventional structure function measurements where they relate directly to this subject. For a more complete discussion of these the reader is referred to the recent reviews of Dydak¹ and Rith².

1. STRUCTURE FUNCTIONS AND DEEP INELASTIC SCATTERING

One of the most direct methods of studying the structure of the nucleon is provided by deep inelastic scattering. The data can be extremely well described in terms of nucleons which consist of fractionally charged quarks which are bound together via the exchange of electrically neutral gluons. In this picture electron, muon and neutrino scattering is described by the incoherent sum of quasi-elastic scatters from the quarks. This scenario originally proposed by Bjorken³ and rapidly supported by experiment⁴ has formed the basis of ~ 15 years of experimental and theoretical effort.

For an incident lepton beam of energy, E , the basic deep inelastic scattering process is illustrated in Fig. 1

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Fig. 1
Deep Inelastic Scattering Process

where the quark and probe kinematics are defined below:

Q^2, ν^2 - invariant mass squared, energy of the probe.

$y = \frac{\nu}{E}$ - relates to the lepton scattering angle in the lepton-nucleon centre of mass.

$x = \frac{Q^2}{2M\nu}$ - fraction of the nucleon momentum carried by the struck quark

The cross-sections in the single photon/boson exchange approximation ⁵ are then given by:

(a) charged lepton (e or μ) scattering:

$$\frac{d\sigma}{dx dy} = \frac{4\pi\alpha^2}{Q^4} ME [xy^2 F_1(x, Q^2) + (1-y-\frac{Mxy}{2E}) F_2(x, Q^2)] \quad (1)$$

(b) neutrino/anti-neutrino scattering:

$$\frac{d\sigma^\nu}{dx dy} = \frac{G^2 ME}{\pi} [xy^2 F_1(x, Q^2) + (1-y-\frac{Mxy}{2E}) F_2(x, Q^2) \pm y(1-\frac{y}{2}) x F_3(x, Q^2)] \quad (2)$$

where F_1 and F_2 are the STRUCTURE FUNCTIONS of the target nucleon defined in a way analogous to the electromagnetic Form Factors G_E and G_M but in general functions of two variables x and Q^2 rather than just Q^2 . A third structure function F_3 appears in the neutrino cross-section because of the non conservation of parity in the weak interaction and its sign changes as $\nu \rightarrow \bar{\nu}$.

F_1 and F_2 are related via the expression:

$$R(x, Q^2) = \frac{F_2(x, Q^2) \left(1 + \frac{Q^2}{v^2}\right) - 2xF_1(x, Q^2)}{2xF_1(x, Q^2)} \quad (3)$$

Thus the unknown physics of the interaction is defined in terms of the structure functions F_1, F_2, F_3 or R, F_2, F_3 .

In the Quark Parton Model (Q.P.M.) picture of the nucleon, F_2 (at large Q^2) is given by the incoherent sum of scattering from the constituents of the nucleon. Thus for μ -nucleon scattering:

$$F_2(x) = \sum_f e_f^2 x q_f(x) \quad (4)$$

where

$q_f(x)$ is the momentum distribution function of the f^{th} quark in the nucleon and e_f is the charge of the f^{th} quark.

Also the constituent quarks have spin $\frac{1}{2}$ so that

$$2xF_1(x) \sim F_2(x)$$

$$\text{and} \quad R(x) \sim 0 \quad (\text{high } Q^2) \quad (5)$$

or more generally, for quarks of mass M_q and transverse momentum P_T :

$$R(x) \approx \frac{4(P_T^2 + M_q^2)}{Q^2} \quad (\text{low } Q^2) \quad (6)$$

and the neutrino and muon (electron) F_2 's are related by:

$$F_2^{\mu N} \approx \frac{5}{18} F_2^{\nu N} \quad (7)$$

Experimentally the structure functions are determined from combinations of the measured charged and neutral lepton cross-sections listed below:

- (a) $\sigma^{\mu N} \rightarrow F_2^{\mu N}$
 - (b) $\sigma^{\nu N} + \sigma^{\bar{\nu} N} \rightarrow F_2^{\nu N}$
 - (c) $\sigma^{\nu N} - \sigma^{\bar{\nu} N} \rightarrow xF_3^{\nu N}$
 - (d) measurements of σ at fixed x, Q^2 values but using different beam energies, $E \rightarrow R$
 - (e) $\sigma^{\bar{\nu} N} - (1-y)^2 \sigma^{\nu N} \xrightarrow[\text{limit } y \rightarrow 1]{} \bar{q}$, the antiquark or sea quark distribution function.
- given R
- (8)

The results in general agree very well in both their x and Q^2 -dependences and the absolute normalisations agree to within 5-7% between different experiments.² In particular the QPM picture is seen to work very well and only a small Q^2 -dependence is seen which can be understood in terms of Quantum Chromodynamic (QCD) radiative corrections.¹ As an example Fig. 2 shows a data compilation for the Q^2 region $10 < Q^2 < 30 \text{ GeV}^2$ plotted as a function of x .⁶ Here one can clearly see the applicability of the QPM $\frac{5}{18}$ factor and also the shape of the sea quark distribution which falls rapidly with x and dies out by $x \sim 0.3-0.4$.

Fig. 2
 F_2 , xF_3 , $\bar{q}$ for the Q^2 region $10 < Q^2 < 30 \text{ GeV}^2$

2. THE EMC EFFECT - WHAT IS IT?

Until recently experimental and theoretical dogma said that for a nucleus of atomic weight A that apart from Fermi motion effects, the nucleus structure function was simply $\frac{1}{A}$ multiplied by the sum of its constituent nucleon structure functions, i.e. for iron

$$F_2^{\text{Fe}}(x) = \frac{1}{56} [26F_2^{\text{P}}(x) + 30F_2^{\text{n}}(x)] \quad (9)$$

where F_2^p and F_2^n are the free proton and nucleon structure functions respectively. However in 1982 the European Muon Collaboration (EMC) observed that the ratio of the structure function $F_2^{\mu N}$ measured on iron when compared to that measured on deuterium deviated from the expected ratio of one by up to 15% and showed a significant x -dependence⁷.

Fig. 3

(a) Ratio $F_2(\text{Fe})/F_2(\text{D}_2)$ without Fermi motion corrections

(b) Fermi motion predictions for various different models

The results are shown in Fig. 3(a) and have been averaged over the available Q^2 range for each value of x . Only the statistical errors are shown but the effect cannot be explained away on the basis of systematic uncertainties as these are less than 7% everywhere. The effect implies that even at large Q^2 the nucleus does not behave as an incoherent superposition of free nucleons. Fermi motion of the nucleons inside the nucleus also does not account for the effect as the correction for deuterium is much smaller than that for iron.⁸ The data points which are NOT corrected for Fermi motion do not follow the trend of the Fermi motion expectation (Fig. 3(b)), indicating that another nuclear phenomenon is at work and that the EMC effect after Fermi motion correction is even larger.

3. THE EMC EFFECT - WHERE ARE WE NOW?

The original EMC announcement was met with some surprise and considerable scepticism. However, shortly afterwards the effect was confirmed by a Rochester-SLAC-MIT group who had gone back and reanalysed some 10 year old steel and aluminium empty target cell data. The data which had originally been taken and used for background subtractions in the E49B and E87 experiments at SLAC provided an ideal way of cross checking the EMC observations as they were taken under completely different conditions and so were subject to completely different systematic uncertainties. When compared to the deuterium data from the same experiments the $\frac{\sigma(\text{Fe})}{\sigma(\text{D}_2)}$ and $\frac{\sigma(\text{Al})}{\sigma(\text{D}_2)}$ ratios revealed the same x-dependence as had been seen by the EMC.¹¹

The publication of these data have stimulated a considerable amount of experimental and theoretical activity and 18 months later much more information is now available. The theoretical progress on the EMC effect will be reviewed by Chris Llewellyn-Smith in a later talk.¹² I will now proceed to review the experimental situation.

Table 1

Collaboration	Beam	Targets	Comments	Ref. No.
EMC	280 GeV μ^+	D ₂ , Fe	$9 \leq Q^2 \leq 170$ original discovery	7
BCDMS	280 GeV μ^+	D ₂ , N ₂ Fe	$40 \leq Q^2 \leq 190$ preliminary	13
SLAC E49B, E87	e^-	D ₂ , Al, Fe	$2 \leq Q^2 \leq 21$	12
SLAC E61	3-18 GeV e^-	D ₂ , C, Cu, Pb	$0.3 \leq Q^2 \leq 2$	14
SLAC E139	8-24.5 GeV e^-	D ₂ , He, Be, C, Al, Ca, Fe, Ag, Au	$4 \leq Q^2 \leq 15$	15 16
CERN WA21	WBB $\nu, \bar{\nu}$	H ₂ Fe	combined BEBC and CDHS ¹⁷ data $\langle Q^2 \rangle \sim 1$	17
CERN WA24	WBB $\nu, \bar{\nu}$	H ₂ , Ne	$\langle Q^2 \rangle \sim 1$	19
CERN WA25/WA59	WBB $\nu, \bar{\nu}$	D ₂ , Ne	$\langle Q^2 \rangle \sim 1$	20 21
CDMS	$\nu, \bar{\nu}$	H ₂ , Fe	$\langle Q^2 \rangle \sim 7$	22
FERMILAB 15'BC	ν	D ₂ , Ne	FERMILAB Ne + BEBC D ₂ data $\langle Q^2 \rangle \sim 1$	23

New, high statistics, measurements of the structure functions from nuclear targets have been made at both high and low Q^2 values by the BCDMS¹³ and E139¹⁵ collaborations at CERN and SLAC. Additional information comes from a variety of lower statistics neutrino experiments which are summarised in Table 1.

3.1 THE X-DEPENDENCE

As the charged lepton data is by far the most precise and extensive let us first consider this. Fig. 4 shows the kinematic range in x and Q^2 covered by the experimental data from which it can be seen that the BCDMS and EMC data at large Q^2 have extensive overlap but are completely separated from the E139 electron data which is at somewhat lower values of Q^2 . Each group have presented data on the ratio iron : deuterium and so this makes a natural point

Fig. 4

$x - Q^2$ ranges for charged lepton data

of comparison. The data are presented in the form of structure function ratios by the two muon experiments where a constant value of 0.0 has been assumed for R in extracting F_2 from the measured cross-sections. The electron data are given as the ratios of cross-sections due to possible worries about the value of R at small values of Q^2 . Note that these are equivalent provided that R is not A -dependent - a fact that still remains to be established (see later).

The results are shown in Figs. 5(a) and (b) for the muon and electron data, respectively. As one can immediately see there is excellent agreement in both shape and absolute normalisation for the region $x \gtrsim 0.25$ but differences are apparent at smaller values of x .

Fig. 5

(a) $F_2(\text{Fe})/F_2(\text{D}_2)$ at large Q^2 from BCDMS and EMC

(b) $\sigma(\text{Fe})/\sigma(\text{D}_2)$ at small Q^2 from various SLAC experiments

First let us consider the high Q^2 data in a little more detail. The EMC and preliminary BCDMS data are entirely in agreement and have nearly identical x dependent slopes of

$$\text{EMC}^7 \quad -0.52 \pm 0.04(\text{stat}) \pm 0.21(\text{syst})$$

$$\text{BCDMS (prelim.)}^{24} \quad -0.56 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$$

A nice feature of the BCDMS and indeed most of the new experiments is that the data were taken simultaneously from both targets so that nearly all systematic uncertainties cancel out in the ratio.

The electron data in Fig. 5(b) come from E49B/E87, E61 and E139 which cover similar but slightly different Q^2 regions. The E61 data are in fact from copper rather than iron, but as the A of the two materials is similar I have included these results for comparison. The data agree well within the quoted systematic errors of 1-2% except for the region $x \lesssim 0.2$ where there are also inconsistencies with the muon data. Beyond $x \sim 0.65$ the nuclear differences

begin to be swamped by the effects of Fermi motion which are rapidly growing in this region.

One could argue that the small x differences as $Q^2 \rightarrow 0$ are the result of a Q^2 -dependence related to nuclear shadowing effects.²⁵ However the current data are insufficient to test this hypothesis as no single experiment spans a sufficiently large Q^2 range at small x .

Fig. 6
WA59/WA25 ν , $\bar{\nu}$ data on $\sigma(\text{Ne})/\sigma(\text{D}_2)$

The neutrino and antineutrino results listed in Table 1 have been presented in the form of the x - and y -dependences of the cross-section ratios. A typical example is shown in Fig. 6 which shows the WA59/WA25 $\bar{\nu}$ ²⁰ and ν ²¹ data on the ratio $\frac{\sigma(\text{Ne})}{\sigma(\text{D}_2)}$ as a function of x . The solid line is the EMC slope fit taken from Fig. 5 which is consistent with the results within errors except for small x region where the data dip below one in a similar manner to the low Q^2 data from E61.

Each of the neutrino results show similar trends with the ratio seen to be below one at small x , rising above one for $x \sim 0.2 \rightarrow 0.4$ and falling below one again for $x \gtrsim 0.4$. This basic shape is not changed if the average Q^2 of the data is increased from $\sim 1 \text{ GeV}^2$ to $\sim 8 \text{ GeV}^2$ by cutting away the low Q^2 events.²⁰ However, in general the results are inconclusive due to lack of statistics and they contribute little information beyond what has been established by the charged lepton data.

3.2. THE A-DEPENDENCE

A new feature of the data on the EMC effect is the study of the Atomic Weight or A-dependence of the cross-section ratios. Recently the E139 collaboration have carried out measurements on the Be, C, Al, Ca, Fe, Ag and Au targets in the kinematic region $0.09 < x < 0.9$ and $2 \leq Q^2 \leq 15 \text{ GeV}^2$ to try to establish whether the EMC effect is A-dependent and/or depends on the nuclear density of the target material.

The results, presented in the form of ratios $\frac{\sigma(A)}{\sigma(D_2)}$, show similar x-dependences for each material with the results consistent with one for $0.1 \lesssim x \lesssim 0.3$ and then falling below one in the manner described above for $0.3 \lesssim x \lesssim 0.8$. If the results are plotted as a function of A at fixed x then a clear A-dependence is seen (Fig. 7(a)) and the variation can be equally well described in terms of a logarithmic decrease in the ratio with increasing A:

$$\frac{\sigma(A)}{\sigma(D_2)} = CA^{\alpha(x)}$$

or linearly with the average nuclear density:

$$\frac{\sigma(A)}{\sigma(D_2)} = a(1 + b(x) \rho(A))$$

Fig. 7

A-dependence of $\sigma(A)/\sigma(D_2)$

(a) E139, BCDMS data for $x = 0.3$ and 0.62

(b) x-dependence of fit parameters α , b from E139

is further supported by the direct ratio of the seas in iron and hydrogen from the CDHS collaboration which is shown in Fig. 8(b).²²

In all cases the experimental errors are large, however one is led to conclude that a large increase in the quark sea, $\bar{q}$ in large A nuclei has been ruled out by these measurements.

Table 2

Collaboration	Ratio	Average Q^2
WA24 ¹⁹	$\frac{\int \bar{q}(\text{Ne}) dx}{\int \bar{q}(\text{H}_2) dx} = 0.95 \pm 0.16$	$\sim 1 \text{ GeV}^2$
WA25, WA59 ²⁰	$\frac{\int \bar{q}(\text{Ne}) dx}{\int \bar{q}(\text{D}_2) dx} = 0.91 \pm 0.06$ 0.85 ± 0.10	$\sim 1 \text{ GeV}^2$ $\sim 8 \text{ GeV}^2 (Q^2 \geq 4.5)$
CDHS ²²	$\frac{\int \bar{q}(\text{Ne}) dx}{\int \bar{q}(\text{H}_2) dx} = 1.10 \pm 0.11 \pm 0.07$	$\sim 7 \text{ GeV}^2$

3.4 THE GLUON STRUCTURE FUNCTION, $G(x)$

By evaluating the Energy-Momentum Sum Rule⁵ it can be shown that only 50% of the momentum of the nucleon is carried by its constituent quarks.

$$\text{i.e.} \quad \int F_2^{\nu N}(x) dx \approx 0.51, \quad 27 \quad \int F_2^{\mu N}(x) dx \approx 0.14 \quad 28$$

The remaining 50% is carried by gluons which couple to the quarks and confine them inside the nucleon. The momentum distribution of the gluons is described by the GLUON STRUCTURE FUNCTION, $G(x)$. Within the framework of Quantum Chromodynamics (QCD) the Q^2 -evolution or scaling violations of $G(x)$ and the standard structure functions R , F_2 and xF_3 can be predicted with great success.

Experimentally $G(x)$ is 'measured' by fitting to the QCD evolution of $F^{\nu N}$ and $\bar{q}^{\nu N}$. The normalisation is fixed by assuming $\int F_2(x) + G(x) dx = 1$ and the shape from $\bar{q}(x)$. There are however many experimental and technical problems with this procedure resulting in large systematic uncertainties at small x . The best determinations of $G(x)$ to date come from the CDHS (ν -Fe data)²⁹ and CHARM (ν -CaCO₃ data)³⁰ collaborations. The results are shown in Fig. 9 from which one can see that there is reasonable agreement within the large uncertainties (shaded regions) on the measurements. The only slight difference is that the CHARM distribution is slightly softer than that of CDHS.

where α , b are x -dependent fit parameters (Fig. 7(b)) and $\rho(A)$ is the average nuclear density.

In addition to the results for iron discussed in the previous section the BCDMS collaboration have also presented preliminary results from N_2 in the kinematic region $0.25 \leq x \leq 0.65$ and $40 \leq Q^2 \leq 190 \text{ GeV}^2$. These are shown for comparison with the W139 data in Fig. 7(a) from which it can be seen that they are in very good agreement with the A -dependence described above.

3.3 LOW x - AN INCREASE IN THE SEA QUARK, $\bar{q}$ DISTRIBUTION?

It has been suggested that the low x enhancement of the ratio $\frac{F_2(\text{Fe})}{F_2(D_2)}$ and the difference, $\Delta = F_2(\text{Fe}) - F_2(D_2)$ seen in the EMC data may be due to a substantial increase in the sea quark distribution in the iron nucleons. This follows from arguments based on the x -dependence of Δ (Fig. 8(a)) which shows a large enhancement in this small x (sea quark) region and only a small depletion in the larger x (valence quark) region.²⁶

Fig. 8

Low x - an increase in $\bar{q}$

(a) Δ -distribution from EMC

(b) $\bar{q}(\text{Fe})/\bar{q}(\text{H}_2)$ from CDHS

Neutrino experiments have direct access to the nucleon $\bar{q}$ distributions via the y -dependence of the neutrino cross section (equation 8(a)). Several groups have used this to determine $\bar{q}$ off of nuclear and nucleon targets and have published the comparisons. The results in the form of x -integrated $\bar{q}$ ratios are summarized in Table 2 and show no evidence for the predicted sea increase. This

Fig. 9

Gluon Structure Functon $G(x)$ at $Q^2 = 10 \text{ GeV}^2$

Recently the EMC collaboration³¹ have tried an alternative approach to try to compare $G(x)$ for iron with $G(x)$ for deuterium. The procedure adopted has been to measure J/ψ production cross-sections off of the two targets and then compare the results. From these it is possible, via the 'Photon-Gluon Fusion' model to unfold $G(x)$ from $\sigma_Y(\gamma N \rightarrow J/\psi)$.³² Here the J/ψ production mechanism is assumed to proceed via the leading order QCD diagram shown in Fig. 10(a) so that σ_Y depends only on ν, Q^2 of the virtual photon and $G(x)$ for the nucleon. The results are model dependent but by taking the ratio of the two cross-sections many of the uncertainties cancel out. The results are shown in Fig. 10(b) for the x range $0.02 < x < 0.08$ and a Q^2 value of $\sim 10 \text{ GeV}^2$. No obvious x -dependence is seen and the results when combined give:

$$\frac{G(x)^{\text{Fe}}}{G(x)^{\text{D}_2}} = 1.44 \pm 0.12(\text{Stat}) \pm 0.20 (\text{Syst})$$

indicating that the gluon distribution in iron in this region is systematically larger than that for deuterium. However, as with the previous results the errors are large and by combining the three sets of results from CDHS, CHARM

and EMC one can only conclude that some tentative indications have been seen that the gluon distribution may be different for different nuclei. For the present the experimental and theoretical uncertainties are too large to give any more definite answer.

Fig. 10

Comparison of Gluon Distribution in Iron and Deuterium

(a) L.O. 'Photon-Gluon Fusion' Graph for J/ψ Production

(b) EMC Results for $G(x)^{Fe}/G(x)^{D_2}$

3.5 IS R A-DEPENDENT?

In this last experimental section I will discuss our current knowledge of the structure function R and attempt to see if the data allow for it to have any nuclear dependence.

It is convenient to divide the data into low and high Q^2 . First let us consider the high Q^2 data - i.e. data for $Q^2 \geq 20$ GeV. Fig. 11 shows the EMC proton data or R which is typical of the measurements in this regime in that it shows little or no visible dependence on ν, Q^2 or x within the errors.^{28,33} For this reason it is more convenient to integrate over all variables and produce a Q^2 - x or Q^2 - ν averaged result. A summary of these results is given in Table 3 from which one may conclude that in addition to a lack of any significant kinematic dependence that R is close to zero. Thus any nuclear dependence at large Q^2 must also be small.

Fig. 11
The Q^2 and ν -dependences of R at large Q^2

Table 3

Collaboration	Beam/Target	R	Comments
EMC ^{28,33}	μp	$-0.010 \pm 0.037 \pm 0.102$	$0.03 \leq x \leq 0.35$ $\langle Q^2 \rangle = 22.5 \text{ GeV}^2$
	μFe	0.03 ± 0.11	
BFP ³⁴	μFe	$-0.06 \pm 0.06 \pm 0.11$	$\langle x \rangle \sim 0.3$ preliminary
CDHS ³⁵	νFe	$\leq 0.039 \pm 0.014 \pm 0.025$	large x limit $\langle Q^2 \rangle = 38 \text{ GeV}^2$
CCFR ³⁴	νFe	$0.100 \pm 0.025 \pm 0.060$	preliminary

Turning now to lower Q^2 measurements one finds that small but non-zero values are found for R and that there are some indications of an x -dependence in the SLAC-MIT electron and CDHS and CHARM neutrino data. These are shown in Fig. 12 together with the muon data from the CHIO collaboration.

Fig. 12

The x-dependence of R at small Q^2

In addition to x-dependence there are indications of small target-dependent differences and it would be tempting to try to interpret these as evidence for a possible nuclear dependence of R. However one must be very careful here as,

Table 4

Collaboration	Beam/Target	R	Comments
SLAC ³⁶	ep	0.22 ± 0.10	$0.1 < x < 0.85$ $\langle Q^2 \rangle \sim 4 \text{ GeV}^2$
	ed	0.24 ± 0.10	
SLAC-MIT ³⁷	ep	$0.138 \pm 0.010 \pm 0.056$	$0.1 < Q^2 < 0.85$ $\langle Q^2 \rangle \sim 4 \text{ GeV}^2$
	ed	$0.175 \pm 0.009 \pm 0.060$	
CHIO ³⁸	μP	$0.52^{+0.25}_{-0.25}$	$x < 0.1$ $\langle Q^2 \rangle \sim 1 \text{ GeV}^2$
CDHS ³⁹	νFe	$0.08 \rightarrow 0.15$	$0.5 < Q^2 < 10 \text{ GeV}^2$ $0.01 < x < 0.15$ (data subset)
CHARM ⁴⁰	$\nu CaCO_3$	$0.32 \rightarrow 0.12$	as for CDHS

with the exception of the electron-proton and electron-deuteron data, the data come from different experiments and cover different x - Q^2 regions. As with the large Q^2 results I have summarised the average R values from these and other comparable experiments in Table 4. From these it is clear that one can argue that at least some of the observed effect may be due to a Q^2 -dependence.

Clearly, in order to proceed further along this line, one needs low Q^2 data from a variety of nuclear targets within a single experiment. This is provided by the E139 experiment discussed earlier and recently this group have attempted to extract values of R from their data.¹⁶ Due to lack of statistics it is not possible to look for kinematic variations and the preliminary results are

Fig. 13

The effect of an A -dependence of R

(a) A -dependence of R

(b) Resulting $F_2(\text{Fe})/F_2(\text{D}_2)$ ratios

presented in the form of averaged R values for each of five different nuclei. These are shown in Fig. 13(a) from which it can be seen that there is a hint of a possible increase in R with A . However due to the size of the errors this is not conclusive and the data are also consistent with an A -independent value of around 0.2

One can nonetheless ask the question what effect such an A -dependence would have if you use it to translate the E139 cross-section ratios into structure function ratios. This has been done in Fig. 13(b) where the measured R difference of 0.15 ± 0.11 (stat) has been used to determine the F_2 's. The result is somewhat interesting in that instead of no low x rise in the ratio one now sees a rise which is entirely consistent with the high Q^2 measurements of the EMC group. Further the data for $x \gtrsim 0.3$ is essentially unchanged thereby retaining the agreement in this region discussed earlier.

Thus one can conclude that the current data on R may give a hint of a possible A -dependence at small Q^2 but that for the present the experimental errors are too large to give any definite answer. If however such a dependence is present then it can explain some of the small x differences between small and large Q^2 measurements.

4. CONCLUDING SUMMARY

Taking account of all of the experimental data now available on structure functions one is forced to conclude that the EMC effect has now been established as an experimental fact and that bound and pseudo-free nucleons within the nucleus do not behave in the same way. In particular the data may be summarised as follows:

- There is excellent agreement between all experiments for the region $x \gtrsim 0.25$. No Q^2 -dependence is observed in this region and beyond $x \sim 0.65$ the nuclear dependence is rapidly swamped by Fermi motion effects.

- A dependence of the effect on the atomic weight, A has been observed in both electron and muon data and the results agree well. The dependence grows approximately in proportion to $\log A$ and can be parameterised equally well in terms of a $\log A$ dependence or a dependence linear in the nuclear density.

- At small values of x the electron, muon and neutrino data disagree ($x \gtrsim 0.25$) but can be made consistent by assuming either a strong Q^2 -dependence or an A -dependence of R . There is however no evidence in the muon data for any Q^2 -dependence for $Q^2 \gtrsim 9 \text{ GeV}^2$ and the smaller Q^2 electron and neutrino data are

inconsistent so that it is difficult to draw any conclusions. The new E139 data do show indications of a possible A-dependence in R but for the present the errors are large and are also consistent with no effect.

- Neutrino measurements of the sea quark distribution in large and small A nucleons tend to rule out any large increase in the sea at small x. Errors are large however and the data could still tolerate a small increase.

- Preliminary comparisons of the gluon distributions in iron and deuterium suggest that the glue in iron could be enhanced by up to 45% over that in deuterium in the small x region.

5. THE EMC EFFECT - WHERE ARE WE GOING TO?

Clearly in order to understand what is going on in the small x region and resolve the outstanding questions about a Q^2 -dependence and/or an R-dependence and/or effects related of a gluon/sea distribution change more high precision data are needed.

The outlook for the future is good in that within the next year or so new high statistics data with a larger Q^2 lever arm will become available from experiments which are running/planned at CERN, FERMILAB (Tevatron) and SLAC. These I have attempted to summarise below.

CERN:

(1) BCDMS Collaboration

- Final results on C, N_2 and Fe at large Q^2 should be available within a period of about one year.

(2) EMC Collaboration

- Low Q^2 ($0.5 \lesssim Q^2 \lesssim 2 \text{ GeV}^2$), low x ($x \lesssim 0.3$) data from a 'shadowing' experiment are being analysed now and first results are expected sometime in the fall of this year. This includes data on H_2 , D_2 , C, Ca, Sn and P6.
- New data covering a large Q^2 range ($1 \lesssim Q^2 \lesssim 190 \text{ GeV}^2$) on D_2 , C, Cu, He, Sn are being taken at present and should help to resolve some of the questions about the Q^2 -dependence of the effect.
- A subset of the collaboration are also considering a new proposal to extend these studies to other nuclei and to study R and hadronic final states.

FERMILAB (Tevatron - 1000 GeV):

E665 Collaboration

- In the spring of 1986 the first data-taking run with the new 650 GeV muon beam will take place and it is currently intended that data will be taken using several nuclear targets.

SLAC

E139 Collaboration

- A subset of this group are discussing a proposal for a new experiment to study the x, Q^2 -dependence of R for D_2 and a comparison with heavy nuclei. This would be run in late 1985 and/or early 1986.

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References

1. F. Dydak, Proc. of Int. Symp. on Lepton and Photon Interactions at High Energies, Cornell, 1983.
2. K. Rith, Proc. of Int. Europhysics Conf. on High Energy Physics, Brighton, 1983.
3. J.D. Bjorken, Phys. Rev. 179, 1547, (1969).
4. W.K.H. Panofsky, Proc. 14th Int. Conf. on High Energy Physics, Vienna, 1968.
5. F.E. Close, An Introduction to Quarks and Partons, Academic Press, 1979.
6. J. Carr, private communication.
7. EMC, J.J. Aubert et al., Phys. Lett. 105B, 403, (1983).
8. A. Bodek, J.L. Richie, Phys. Rev. D23, 1970, (1981), Phys. Rev. D24, 1400, (1981).
A. Bodek, Univ. Rochester preprint UR853, COO-3065-365, (1983).
9. L.L. Frankfurt, M.I. Strikman, Phys. Rep. 76C, 215, (1981).
10. G. Berlاد et al., Phys. Rev. D22, 1547, (1980).
11. A. Bodek et al., Phys. Rev. Lett. 50, 1431, (1983), Phys. Rev. Letts. 51, 534, (1983).

12. C.H. Llewellyn-Smith, 'Nuclear Effects in Deep Inelastic Scattering', talk given at this conference.
13. Bologna-CERN-Dubna-Munchen-Saclay, A.C. Benvenuti et al., paper submitted to XXII Int. Conf. on High Energy Physics, Leipzig, 1984.
14. S. Stein et al., Phys. Rev. D7, 1362, (1973).
15. R.G. Arnold et al., SLAC-PUB-3257, (1983).
16. R.G. Arnold, private communication.
17. H. Grässler et al., paper submitted to Int. Symp. on Lepton and Photon Interactions at High Energies, Cornell, 1983. Paper No. C-206.
18. CERN-Dortmund-Heidelberg-Saclay, H. Abramowicz et al., Z. Phys. C17, 283, (1983).
19. M.A. Parker et al., Nucl. Phys. B232, 1, (1983).
20. A.M. Cooper et al., Phys. Lett. 141B, 133, (1984).
21. A.M. Cooper, private communication.
22. H. Abramowicz et al., CERN EP/84-57, (1984).
23. A.E. Astratyan et al., ITEP 83-110, (1983).
24. R. Voss, talk presented at XI Int. Conf. on Neutrino Physics and Astrophysics, Dortmund, 1984.
25. A. Bodek } Proc. XIV Int. Symp. on Multiparticle Dynamics, Lake
A.W. Edwards } Tahoe, June 1983, and references contained therein.
26. R.L. Jaffe, Phys. Rev. Lett. 50, 228 (1983).
27. P.C. Bosetti et al., Nucl. Phys. B203, 362, (1982).
28. S.J. Wimpenny, talk presented at Int. Europhysics Conf. on High Energy Physics, Brighton, (1983).
29. H. Abramowicz et al., Z. Phys. C12, 289, (1982).
30. F. Bergsma et al., Phys. Lett. 123B, 269, (1983).
31. EMC, J.J. Aubert et al., 'A Measurement of the Difference Between the Single Nucleon Cross-Sections for J/ψ Muoproduction in Iron and Hydrogen/Deuterium Targets', in preparation.
32. T. Weiler, Phys. Rev. Lett. 44, 304, (1980).
33. EMC, J.J. Aubert et al., Phys. Lett 121B, 87, (1983).
34. A. Bodek, Rapporteur talk presented at XI Int. Conf. on Nuetrino Physics and Astrophysics, Dortmund, (1984).
35. H. Abramowicz et al., Z. Phys. C17, 283, (1983).
36. M.D. Mestayer et al., SLAC-PUB-2933, (1982).
37. A. Bodek et al., Phys. Rev. D20, 1471, (1979).
38. B.A. Gordon et al., Phys. Rev D20, 2645, (1979).
39. H. Abramowicz et al., Phys. Lett. 107B, 141, (1981).
40. F. Bergsma et al., CERN-EP/84-08, (1984).