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The Nucleon Structure from Fixed Target Experiments

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Abstract

A review is presented of recent experimental results on the internal structure of protons and neutrons, with emphasis on deep inelastic electron, muon, and neutrino scattering. The topics discussed include new results on unpolarised nucleon structure functions, tests of the Quark-Parton Model, determinations of the strong coupling constant and the gluon distribution, nuclear effects and shadowing, and new results on deep inelastic scattering of polarised charged leptons on polarised targets.

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1 Introduction

The scope of deep inelastic scattering physics has changed considerably over the last year with the advent of the first electron-proton storage ring HERA. First results from this new machine have been reported at this conference [1, 2]. At the same time, fixed target deep inelastic scattering experiments are slowly coming to a halt, with the notable exception of scattering on polarised targets (Section 6). However, the analysis of recent experiments will continue for a good while and will produce a wealth of more data. Fixed target experiments are complementary to HERA in kinematic range and have attained in recent years integrated luminosities that will probably never be matched by a storage ring machine. Also, neutrino scattering contributes unique information that is accessible in fixed target experiments only. Both HERA and fixed target experiments will therefore complement each other in providing a firm basis for our understanding of the nucleon structure also in the future.

The present paper is not intended to be a complete review of nucleon structure physics but focuses on what I believe are significant experimental advances of the last 1–2 years. For an introduction into the formalism and in-depth discussions of many topics which I have to neglect, the reader is referred to more comprehensive review papers [3, 4, 5, 6] and to previous conference proceedings in this series.

2 New Results on Nucleon Structure Functions

Major new sets of data on nucleon structure functions have recently become available from the muon scattering experiment NA37 of the NMC Collaboration at CERN and from the neutrino experiments E744 and E770 of the CCFR Collaboration at Fermilab.

Muon Scattering

The recent results obtained by the NMC Collaboration on the structure function $F_2^\mu(x, Q^2)$ [7] are a major advance in three respects (Fig. 1). First, they solve once and for all the problem of the unfortunate discrepancy between earlier CERN muon scattering data from the BCDMS and EMC collaborations [8] in favour of the BCDMS data. Second, the good kinematic acceptance of the NMC apparatus combined with a relatively low beam energy of 90 GeV now link the muon data to the earlier SLAC electron scattering data at low Q^2 . Third, NMC also has extended the kinematic range to smaller values of Bjorken x by almost one order of magnitude, thus building an important bridge to the HERA results and providing a powerful constraint for the all-important parametrisations of parton distributions [11]. The enlarged kinematic range also makes this a powerful set of data to determine the gluon structure function of the nucleon (Section 4).

Neutrino Scattering

The CCFR Collaboration has presented preliminary results from experiments with the Fermilab wide-band neutrino beam [12]. These are high statistics measurements of the structure functions $F_2^\nu(x, Q^2)$ and $xF_3^\nu(x, Q^2)$ from 1,280,000 ν_μ and 270,000 $\bar{\nu}_\mu$ charged current interactions on iron after cuts. These are the most accurate deep inelastic neutrino data now available (Fig. 2). Scaling violations are clearly observed in these data that will be discussed in Section 4.

The CCFR data on $F_2^\nu(x, Q^2)$ are compared to charged lepton data for two selected x bins in Fig. 3. The charged lepton data were corrected for quark charges, nuclear effects, and the excess of the strange sea in the neutrino structure function [13]. Whereas there is excellent agreement between the charged lepton and neutrino data in the region

Figure 1: The deep inelastic structure function $F_2^\mu(x, Q^2)$ measured by NMC with a deuterium target. Also shown are earlier electron scattering data from SLAC (9) and muon data from the BCDMS Collaboration at CERN (10). Only statistical errors are shown.

Figure 2: The deep inelastic structure function $F_2^\nu(x, Q^2)$ measured by CCFR with an iron target. The solid lines show a perturbative QCD fit. Only statistical errors are shown.

Figure 3: $F_2^\nu(x, Q^2)$ measured by CCFR with an iron target compared to data from charged lepton scattering on deuterium from BCDMS, SLAC and NMC, for $x = 0.080$ (top) and $x = 0.275$ (bottom). The charged lepton data are corrected for quark charges, nuclear effects, and the excess of the strange sea in the neutrino structure function.

of intermediate and large x , there is a discrepancy of 5 to 10% in the small x region. This is probably related to experimental systematics in the calibration and normalisation of the data, to different methods of correcting for the structure function $R = \sigma_L/\sigma_T$ and the charm threshold, and different radiative corrections. CCFR is presently finalising their analysis with the aim of decreasing the systematic errors and applying the phenomenological corrections such that the results can be more directly compared to the charged lepton data.

Charm Production by Neutrinos

It has also been argued that the small x discrepancy between neutrino and charged lepton data is due to a substantial underestimate of the strange sea contribution to $F_2^\nu(x, Q^2)$ [14]. CCFR has measured the strange sea distribution in the nucleon by studying the production of opposite sign dimuons in charged current neutrino scattering,

$$\nu_\mu N \rightarrow \mu^- DX, \quad D \rightarrow \mu^+ \nu_\mu X'.$$

The cross section for this process is dominated in leading order QCD by $s, d \rightarrow c$ transitions in the nucleon; at next to leading order, photon-gluon fusion also gives a sizeable contribution. The cross section for this process can be expressed as

$$\frac{d^3\sigma(\nu N \rightarrow \mu^- \mu^+ X)}{d\xi dy dz} = \frac{d^2\sigma(\nu N \rightarrow cX)}{d\xi dy} D(z) B(c \rightarrow \mu) \quad (1)$$

where the slow rescaling variable $\xi = x(1 + m_c^2/Q^2)$ accounts for threshold effects due to the charm quark mass m_c , $d^2\sigma(\nu N \rightarrow cX)/d\xi dy$ is the hard scattering cross section [15], $D(z)$ the D fragmentation function, and $B(c \rightarrow \mu)$ the semileptonic branching ratio.

CCFR determines the strange contribution to the nucleon sea by a fit to 5030 ν and 1060 $\bar{\nu}$ induced events after cuts. Parametrising the strange sea as $xs(x) \propto x\bar{q}(x)(1-x)^\alpha$, where $\bar{q}(x)$ is the light quark sea, preliminary results from a next-to-leading order QCD fit in the $\overline{MS}$ scheme are $\alpha = -0.27 \pm 0.60 (stat.) \pm 0.35 (syst.)$ and, for the strange sea content κ , $\kappa = 2 \int xs(x)dx / \int x[\bar{u}(x) + \bar{d}(x)]dx = 0.435 \pm 0.058 \pm 0.012$. The strange sea is thus similar in shape to the light quark sea and CCFR concludes that its magnitude can *not* explain the observed discrepancy to the charged lepton data [16]. From the same fit, they determine the charm quark mass to $m_c = 1.61 \pm 0.20 \pm 0.12$ GeV and the semileptonic branching ratio to $B(c \rightarrow \mu) = 0.102 \pm 0.007 \pm 0.004$.

3 Quark-Parton Model Tests

Quark Charges

CCFR has used their data on F_2^ν in combination with muon data for a new test of the Standard Model quark charges. In the Quark-Parton Model (QPM), muon and neutrino structure functions measured on isoscalar targets are related by the well-known expression

$$\frac{F_2^\mu(x)^*}{F_2^\nu(x)} = \frac{5}{18} \left[1 - \frac{3}{5} \frac{s(x) + \bar{s}(x)}{q(x) + \bar{q}(x)} \right] \quad (2)$$

where $5/18$ is the average squared charge of the valence quarks and the term in square brackets accounts for different distributions of strange and charm quarks; $c = 0$ is assumed in Eq. (2). This correction is sizeable only at small x where it can be as large as 10%. The experimental structure function ratio is shown in Fig. 4. The comparison to carbon and deuterium data from BCDMS is perfectly consistent with the Standard Model quark charges, whereas the CCFR/EMC comparison reflects the BCDMS-EMC discrepancy mentioned in Section 2.

The Gross-Llewellyn Smith Sum Rule

Sum rules are amongst the most stringent predictions of the QPM, although no experiment can explore the complete kinematic range in x that is needed for their verification. CCFR has made a careful evaluation of the Gross-Llewellyn Smith sum rule which, including QCD radiative corrections at leading order, reads [17]

$$S_{GLS} = \int_0^1 \frac{x F_3(x, Q^2) dx}{x} = 3 \left[1 - \frac{\alpha_s(Q^2)}{\pi} \right] = 2.66 \pm 0.04. \quad (3)$$

The numerical prediction refers to $\Lambda_{\overline{MS}}^{(4)} = 210 \pm 50$ MeV and $Q^2 = 3$ GeV² (see Section 4 for the terminology).

They find [18]

$$S_{GLS} = 2.50 \pm 0.018 (stat.) \pm 0.078 (syst.).$$

The systematic error is dominated by uncertainties of the absolute neutrino flux normalisation, and of the extrapolation to $x \rightarrow 0$ which is delicate because of the $1/x$ term in the integral (Fig. 5). This result is lower than the prediction by 1.8 standard deviations. The discrepancy is covered, at least partly, by theoretical uncertainties due to the neglect of higher order corrections, and of higher twist and target mass effects.

Figure 4: $F_2^\nu(x)$ measured by CCFR with an iron target, compared to $F_2^\mu(x)$ measured on deuterium and carbon by BCDMS, and on iron by EMC. The deuterium data are corrected for nuclear effects. In the numerical results for the average ratio, the error in square brackets accounts for the overall normalisation uncertainties of the data.

Figure 5: CCFR test of the Gross-Llewellyn Smith sum rule. The dashed line indicates the parametrisation of the data used to evaluate the integral and the solid line illustrates the convergence of the integral at small x .

Figure 6: The cross section ratio σ_n/σ_p measured by E665. The error bars show the statistical errors and the shaded band the systematic errors. Also shown are previous results on $F_2^n(x)/F_2^p(x)$ from NMC (19) and BCDMS (25). The solid line is a prediction based on a vector dominance model (26).

The Neutron/Proton Structure Function Ratio and the Gottfried Sum Rule

Historically, the ratio $F_2^n(x)/F_2^p(x)$ has been another important quantity to test elementary predictions of the Quark-Parton Model. Later, it became an important constraint for QCD fits that determine parton distributions from experimental structure functions, especially since the advent of very precise NMC data from simultaneous measurements on proton and deuterium targets [19, 20].

The Fermilab muon scattering experiment E665 has recently presented a first measurement of this ratio which is less precise than the NMC data but covers a much larger kinematic range in x [21]. The data were evaluated as a cross section ratio σ_n/σ_p , which is equivalent to the structure function ratio provided that $R = \sigma_L/\sigma_T$ is the same for protons and neutrons. The E665 data bridge the gap between the deep inelastic and the photoproduction regime. They are consistent with unity for $2 \cdot 10^{-5} < x < 10^{-1}$, and indicate that within the errors there is no shadowing in deuterium down to the smallest x measured in this experiment. (Fig. 6).

Another QPM prediction that has recently been in the focus of much interest is the Gottfried sum rule [22]. In terms of the proton and neutron structure functions $F_2^p(x)$ and $F_2^n(x)$, this sum rule can be written as

$$S_G = \int_0^1 \frac{[F_2^p(x) - F_2^n(x)]dx}{x} = e_u^2 - e_d^2 + \frac{2}{3} \int_0^1 [\bar{u}(x) - \bar{d}(x)]dx \quad (4)$$

where we have assumed isospin symmetry of the quark distribution functions, i.e. $u^p(x) \equiv d^n(x)$ etc. The Gottfried sum rule can thus be interpreted as a test of the flavour symmetry of the quark sea in the nucleon.

Figure 7: NMC test of the Gottfried sum rule. The closed symbols show the experimental data and the open symbols the extrapolation to $x \rightarrow 0$. Also shown are the extrapolated value S_G and the naive QPM prediction.

The NMC Collaboration has recently updated their test of this sum rule [23] by a new analysis [20] that incorporates a refined evaluation of $F_2^n(x)/F_2^p(x)$ needed to extract the neutron from the deuterium structure function, a new fit to $F_2^d(x)$ including their own data [7], and improved radiative corrections (Fig. 7). NMC finds

$$S_G = 0.258 \pm 0.017,$$

which is higher than their first result but still more than four standard deviations below the “naive” prediction that $S_G = e_u^2 - e_d^2 = 1/3$. The ratio $F_2^n(x)/F_2^p(x)$ used in this analysis is somewhat smaller than unity down to the smallest values of x ($x \geq 0.007$), indicating a small shadowing effect in deuterium at the 5% level. Such an effect would not be visible within the present errors of the E665 data (Fig. 6). If such a shadowing correction would be applied to the deuterium data used to extract F_2^n , the Gottfried sum S_G would decrease again by 0.01 ... 0.04.

The violation of the Gottfried sum rule has triggered considerable theoretical interest, a review of which is beyond the scope of this paper. On the experimental side, independent information is provided by measurements of the Drell-Yan process $q\bar{q} \rightarrow \mu^+\mu^-$ in hadron-hadron scattering where, at large x ,

$$R(x) = \frac{\sigma_{pn \rightarrow \mu\mu}(x)}{\sigma_{pp \rightarrow \mu\mu}(x)} = \frac{\bar{d}(x)}{\bar{u}(x)} \quad (5)$$

Since there is no free neutron target, such experiments compare cross sections measured on isoscalar targets and on heavy targets with a large neutron excess. Results from Fermilab experiment E772, from scattering of 800 GeV protons on deuterium, carbon and tungsten

targets, show no conclusive evidence for flavour symmetry violation [24]. More Drell-Yan data are expected soon from CERN experiment NA51, and from experiment E866 approved at Fermilab.

4 The strong coupling constant and the gluon distribution

High statistics measurements of $F_2(x, Q^2)$ and $xF_3(x, Q^2)$ and sophisticated QCD analyses have firmly established the validity of the Altarelli-Parisi equations [27] as the correct description of scaling violations observed in deep inelastic scattering [6, 28, 29]. The emphasis of QCD studies in this field has therefore gradually shifted from qualitative QCD tests to accurate determinations of the strong coupling constant α_s and of the gluon distribution.

The Strong Coupling Constant from Deep Inelastic Scattering

Both the NMC and CCFR Collaborations have performed a detailed perturbative QCD analysis of their recent measurements discussed in Section 2. Both groups use next-to-leading order (NLO) fits to determine the QCD mass scale Λ , the strong coupling constant, and to estimate the gluon distribution in the nucleon.

In the jargon of QCD, the valence quark structure function $xF_3(x, Q^2)$ is a linear combination of non-singlet quark distributions in flavour space. Its Q^2 evolution is described by a single Altarelli-Parisi equation that depends on Λ as the only free parameter; it is therefore a particularly clean tool to determine α_s . In their analysis [16], CCFR exploits the fact that, to a very good approximation, $F_2(x, Q^2) \approx F_3(x, Q^2)$ at large x where the quark sea has died out and F_2 also becomes a valence quark distribution. Since F_2 is measured with much better statistical accuracy, it is used in this analysis to replace xF_3 for $x > 0.4$ (Fig. 8). The result of this fit is

$$\Lambda_{\overline{MS}}^{(4)} = 210 \pm 28 \text{ (stat.)} \pm 41 \text{ (syst.) MeV}$$

where the subscript $\overline{MS}$ refers to the renormalisation scheme used to compute the QCD splitting and coefficient functions and the superscript (4) to the number of active flavours used in the QCD fit. This corresponds to a strong coupling constant at the Z mass of

$$\alpha_s(M_Z^2) = 0.111 \pm 0.002 \text{ (stat.)} \pm 0.003 \text{ (syst.)}.$$

The structure function $F_2(x, Q^2)$ is, in general, a linear combination of both flavour singlet and non-singlet quark distributions. Its Q^2 evolution is described by a set of coupled Altarelli-Parisi equations that also depend on the gluon distribution. CCFR has recently presented preliminary results from a combined fit to $F_2(x, Q^2)$ and $xF_3(x, Q^2)$ that gives

$$\begin{aligned} \Lambda_{\overline{MS}}^{(4)} &= 225 \pm 30 \text{ (stat.)} \pm 40 \text{ (syst.) MeV} \\ \alpha_s(M_Z^2) &= 0.113 \pm 0.002 \text{ (stat.)} \pm 0.003 \text{ (syst.)}. \end{aligned}$$

The gluon distribution from this analysis will be discussed in the following section.

NMC has recently published a detailed QCD analysis of their F_2 data measured with hydrogen and deuterium targets [30]. Since these data are centered at a lower average Q^2 , NMC makes an allowance for non-perturbative higher twist contributions to the observed scaling violations at small Q^2 , using an *ansatz*

$$F_2(x, Q^2) = F_2^{LT}(x, Q^2)[1 + H(x)/Q^2] \quad (6)$$

Figure 8: Scaling violations $d \ln xF_3 / d \ln Q^2$ observed in the CCFR data. Scaling violations of F_2 are also shown for $x > 0.4$. Errors are statistical only. The solid line is the non-singlet QCD fit discussed in the text.

Figure 9: Scaling violations $d \ln F_2 / d \ln Q^2$ observed in the NMC deuteron data (cf. Fig. 1). Errors are statistical only. The shaded area illustrates the contribution of the gluon distribution to the scaling violations. The dashed curve shows the QCD fit to the leading twist contribution $d \ln F_2^{LT} / d \ln Q^2$ and the solid line the complete QCD fit including the higher twist contribution discussed in the text.

where the leading twist structure function F_2^{LT} follows the Altarelli-Parisi equations. The higher twist coefficients $H(x)$ were taken from an earlier QCD analysis of the combined BCDMS and SLAC proton and deuteron data [31], and extrapolated to smaller values of x where necessary. A combined flavour singlet and non-singlet fit to the proton and deuteron data gives an excellent description of the data; it is shown in Fig. 9 for the example of the deuteron. NMC prefers to fit α_s rather than Λ at the average Q^2 of their data:

$$\alpha_s(Q^2 = 7 \text{ GeV}^2) = 0.264 \pm 0.018 \text{ (stat.)} \pm 0.070 \text{ (syst.)} \pm 0.013 \text{ (h.t.)}$$

where the “h.t.” term is an uncertainty due to the higher twist corrections. This corresponds to

$$\alpha_s(M_Z^2) = 0.117_{-0.016}^{+0.011}.$$

This result has significantly larger errors than e.g. the CCFR data because the NMC data are kinematically centered at small x where the scaling violations are mostly governed by the gluon distribution (Fig. 9). The strong point of this analysis is indeed the determination of $xG(x)$ that is discussed in the following section.

Recent NLO results on $\alpha_s(M_Z^2)$ from deep inelastic scattering experiments are summarised in Table 1. The first entry in this table is a detailed QCD analysis by Virchaux and Milsztajn of the combined SLAC and BCDMS measurements of $F_2(x, Q^2)$ with hydrogen and deuterium targets that is well documented [31, 6] and not discussed here. This analysis also contains an estimate of a “theoretical” uncertainty due to the neglect of higher order terms in the perturbative QCD expansions, which can be absorbed into a redefinition of the renormalisation scale Q and is therefore often referred to as “scale uncertainty”. CCFR and NMC have not yet evaluated this error but it can be assumed that the SLAC/BCDMS estimate is valid, to a very good approximation, also for the other data sets.

These three determinations of $\alpha_s(M_Z^2)$ are clearly in excellent agreement. Earlier results have been omitted since they have either significantly larger errors or originate from fits of poor quality [32]. It is therefore fair to combine them into a “world average” $\alpha_s(M_Z^2)$ from deep inelastic scattering

$$\alpha_s^{DIS}(M_Z^2) = 0.112 \pm 0.005$$

where the error contains the scale uncertainty. An almost identical result has been obtained by Martin, Roberts and Stirling [33] from the analysis of a combination of data similar to the one used here. They also include an estimate of the scale uncertainty and obtain $\alpha_s^{DIS}(M_Z^2) = 0.111_{-0.005}^{+0.004}$.

Note that the errors of these results are very similar to those of the combined LEP data [34]. The LEP experiments have by now outperformed the deep inelastic experiments in experimental accuracy but still appear to be plagued by a larger scale uncertainty, with the net result that the total errors are comparable at present.

Recent Results on the Gluon Distribution

As mentioned earlier, perturbative QCD fits to flavour singlet structure functions depend on the distribution of gluons in the nucleon. It can be determined as part of such fits provided one supplies an a priori parametrisation of its shape. The most simple *ansatz* one can make is

$$xG(x, Q_0^2) = C(1 - x)^\eta, \quad (7)$$

Table 1: Recent results on the strong coupling constant from deep inelastic scattering

Experiment(s)	$\alpha_s(M_Z^2)$
BCDMS + SLAC	0.113 ± 0.003 (exp.) ± 0.004 (th.)
NMC	$0.117^{+0.011}_{-0.016}$ (exp.)
CCFR (non-singlet analysis)	0.111 ± 0.003 (exp.)

Figure 10: The gluon distribution $xG(x)$ of the nucleon from recent flavour singlet fits by CCFR (preliminary) and NMC. Both fits are evolved to a common $Q_0^2 = 5 \text{ GeV}^2$.

and is motivated by the fact that the gluon distribution is expected to be a radiative spectrum. It has given acceptable fits to many data, and has also been employed by CCFR at a reference $Q_0^2 = 5 \text{ GeV}^2$ in their recent analysis [12]. In the NMC analysis [30] which covers a much larger kinematic range on a log x scale (Fig. 9) it was found for the first time that this simple form is not adequate at x much smaller than 0.01. NMC therefore prefers a parametrisation

$$xG(x, Q_0^2) = C(1-x)^\eta(1 + c_1w + c_2w^2 + c_3w^3) \quad (8)$$

at $Q_0^2 = 7 \text{ GeV}^2$, where

$$w = 0.1 \ln(1 + e^{10-100x}) \text{ for } x \leq 0.1, \quad w = 0 \text{ for } x > 0.1;$$

they do not determine α_s simultaneously but assume a fixed $\alpha_s(Q_0^2) = 0.240$, corresponding to $\alpha_s(M_Z^2) = 0.113$. The NMC and CCFR results are compared in Fig. 10. Both are in good agreement with earlier fits to deep inelastic scattering data.

NMC has also determined the gluon distribution from inelastic J/ψ production [35]

$$\mu + N \rightarrow J/\psi + X$$

Figure 11: The gluon distribution determined by EMC and NMC from inelastic J/ψ production at $Q^2 = M_{J/\psi}^2 = 9 \text{ GeV}^2$. The shaded band shows the NMC scaling violation analysis of Fig. 10, but evolved to the same $Q^2 = 9 \text{ GeV}^2$.

Figure 12: The gluon distribution as determined by WA70 from a next-to-leading order analysis at $Q^2 = 7 \text{ GeV}^2$. The shaded band shows the NMC scaling violation analysis of Fig. 10, but evolved to the same $Q^2 = 7 \text{ GeV}^2$. Note the linear scale in x ; the wiggle in the NMC error band is an artefact of the parametrisation used.

Table 2: Recent results on parametrisations of the gluon distribution from next-to-leading order QCD analyses. The NMC results refer to the parametrisation of Eq. (8), all others to Eq. (7).

Experiment	Q_0^2 (GeV ²)	C	η	c_i
NMC	7	$3.78^{+1.55}_{-0.05}$	$7.43^{+3.18}_{-1.04}$	$c_1 = -0.105^{+0.310}_{-1.410}$ $c_2 = 0.385^{+2.294}_{-0.317}$ $c_3 = -0.283^{+0.254}_{-1.386}$
CCFR (prel.)	5		$4.45^{+1.65}_{-1.15}$	
NMC/EMC J/ ψ	9	2.4 ± 0.4	5.1 ± 0.9	
WA70 (pp)	2	2.0 ± 0.4	$3.7 \pm 0.8 \pm 0.8$	
UA6 (pp) (prel.)	2		$3.72^{+0.19}_{-0.16} \pm 0.6$	
UA6 ($p\bar{p}$) (prel.)	2		$4.13^{+0.27}_{-0.23} \pm 1.0$	

which in QCD is thought to proceed mostly via photon-gluon fusion into charm-anticharm pairs, $g\gamma \rightarrow c\bar{c}$. Results from a NLO analysis are in good agreement with similar work by the EMC Collaboration [36] and with their own analysis of scaling violations (Fig. 11). Finally, several proton (antiproton) scattering experiments have obtained a gluon distribution from measurements of direct photon production

$$p(\bar{p}) + p \rightarrow \gamma + X$$

which, at leading order, is dominated by the QCD Compton process $gq \rightarrow \gamma g$. New NLO results have been submitted to this conference by the WA70 [37] (Fig. 12) and UA6 [38] Collaborations at CERN. Both the J/ ψ and the direct photon analyses also use the simple parametrisation of Eq. (7). All results on the gluon distribution discussed here are summarised in Table 2. A more complete and very useful compilation of parametrisations of the gluon distribution can be found in Ref. [37].

5 Nuclear effects and shadowing

Over the last few years, the experimental study of nuclear effects in deep inelastic scattering has gradually shifted to the region of small Bjorken x , often referred to as the shadowing region. This is a vast field and this brief review will be limited to a few selected highlights [39].

The Fermilab muon experiment E665 has nowadays the best acceptance in the small x region, thanks to a powerful small angle trigger system and a high beam energy. E665 has recently presented new preliminary data on cross section ratios σ^A/σ^d , where d is the deuteron and A stands for carbon, calcium, and lead [40]. The data confirm earlier observations by E665 and by the NMC that shadowing appears to saturate below 10^{-2} , and that there is only little if any Q^2 dependence in shadowing for fixed values of x (Figs. 13 and 14). The latter effect favours parton recombination models of shadowing in which low momentum partons in the nucleon fuse into one parton of higher momentum, thus depleting the low x region. A clear increase with nuclear mass is also observed.

NMC has presented new results on structure function ratios for beryllium, aluminium, calcium, iron, and tin compared to carbon [41] (Fig. 15). In these data, there is a hint to a universality of the value of x where shadowing turns into antishadowing, i.e. $F_2^A(x) = F_2^C(x)$, which is $x \simeq 5 \cdot 10^{-2}$ independent of A . Based on the same data, NMC has also made a very detailed study of the A dependence of the structure function ratio F_2^A/F_2^C (Fig. 16).

Figure 13: Cross section ratios σ^A/σ^d vs. x measured by E665 for $A = C, Ca,$ and Pb (preliminary). The shaded bands indicate the systematic errors.

Figure 14: Cross section ratios σ^A/σ^d vs. Q^2 measured by E665 for $A = C, Ca,$ and Pb (preliminary).

Figure 15: Structure function ratios $F_2^A(x)/F_2^C(x)$ measured by NMC. Earlier data from SLAC are also shown.

Figure 16: The A dependence of the structure function ratio $F_2^A(x)/F_2^C(x)$, parametrised as $\beta = d(F_2^A/F_2^C)/d \ln A$, vs. Bjorken x from NMC and SLAC data.

Figure 17: Cross section ratios σ^A/σ^d vs. x measured by E665 on $A = C, Ca$, and Pb , for events with 1 and 2 current jets in the final state (preliminary).

E665 has also started to search for shadowing in exclusive channels. As an example, Fig. 17 shows preliminary results from a study of jet production in carbon, calcium, and lead [42]. There is a clear indication that shadowing is enhanced for events with two current jets when compared to 1-jet events. Indications for shadowing have also been observed in exclusive ρ production.

6 Polarised deep inelastic scattering

The physics of deep inelastic scattering with polarised high energy electron and muon beams is experiencing a Renaissance, following the seminal results obtained by the EMC on the spin structure function of the proton. The EMC result had raised questions about the understanding of the dynamics of the nucleon spin at the parton level which required more experimental information to be resolved theoretically. New data have become available this year, which include for the first time results on the internal spin structure of the neutron.

Sum Rules for the Spin Structure Function g_1

Experimental efforts in the field of polarised deep inelastic scattering focus very much on the test of sum rules related to the spin-dependent structure function $g_1(x)$ of the proton and the neutron. This structure function has a straightforward interpretation in the QPM, similar to the unpolarised structure functions:

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^+(x) - q_i^-(x)], \quad (9)$$

where $q_i^+(x)$ ($q_i^-(x)$) is the density of quarks with spin parallel (antiparallel) to the nucleon spin.

The most general sum rule prediction for g_1 , and one of the most fundamental predictions of the QPM indeed, is the celebrated Bjorken sum rule for the difference of the first moments of g_1^p and g_1^n [43],

$$\Gamma_1^p - \Gamma_1^n = \int_0^1 [g_1^p(x) - g_1^n(x)] dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right|, \quad (10)$$

where g_A and g_V are the axial-vector and vector weak coupling constants of nuclear beta decay. In this form, the sum rule was derived by Bjorken from light cone algebra and from very general assumptions on the partonic structure of the weak and electromagnetic hadronic currents. Nowadays, the sum rule (10) is understood as a rigorous QCD prediction in the limit $Q^2 \rightarrow \infty$. At finite values of Q^2 and in lowest order QCD [44],

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_s(Q^2)}{\pi} \right]. \quad (11)$$

Separate sum rules for the proton and the neutron were derived by Ellis and Jaffe for the proton and the neutron [45]. Ignoring QCD radiative corrections, they predict for the first moments of g_1^p and g_1^n :

$$\Gamma_1^p = \int_0^1 g_1^p(x) dx = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left[+1 + \frac{5}{3} \frac{F/D - 1}{F/D + 1} \right] \quad (12)$$

and

$$\Gamma_1^n = \int_0^1 g_1^n(x) dx = \frac{1}{12} \left| \frac{g_A}{g_V} \right| \left[-1 + \frac{5}{3} \frac{F/D - 1}{F/D + 1} \right], \quad (13)$$

where F (D) are the antisymmetric (symmetric) $SU(3)$ couplings measurable in hyperon decays. These sum rules are *not* rigorous QCD predictions. They are less fundamental than the Bjorken sum rule since they assume exact flavour $SU(3)$ symmetry of the baryon octet decays, and zero net polarisation of the sea of strange quarks and heavier flavours.

Cross Section Asymmetries

Since the spin-dependent structure functions give only a small contribution to the measurable cross sections [46], it is customary to evaluate them from measurements of cross section asymmetries in which the unpolarised part cancels. In the most simple case where both the beam and the target are longitudinally polarised, this asymmetry is

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \quad (14)$$

where $\sigma^{\uparrow\downarrow}$ and $\sigma^{\uparrow\uparrow}$ are the cross sections for opposite and equal spin directions, respectively. This is the only configuration of beam and target polarisations which so far has been studied experimentally. It can be shown that

$$A = D[A_1 + \eta A_2], \quad (15)$$

where D and η are kinematic factors and where

$$A_1(x) = \frac{g_1(x)}{F_1(x)} = \frac{\sum_i e_i^2 [q_i^+(x) - q_i^-(x)]}{\sum_i e_i^2 [q_i^+(x) + q_i^-(x)]}. \quad (16)$$

A_1 and A_2 can also be interpreted as virtual photon-nucleon asymmetries

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}, \quad (17)$$

$$A_2 = \frac{2\sigma_{TL}}{\sigma_{1/2} + \sigma_{3/2}}, \quad (18)$$

where $1/2$ and $3/2$ are the total spin projections in the direction of the virtual photon, and σ_{TL} is a cross section arising from the interference of amplitudes for longitudinal and transverse polarised virtual photons. The following bounds can be derived for A_1 and A_2 [47]:

$$|A_1| \leq 1, \quad |A_2| \leq R \quad (19)$$

where $R = \sigma_L/\sigma_T$; for this reason, A_2 is expected to give a small contribution to A and is usually ignored.

New Experimental Results on Spin Structure Functions

The EMC measurement of $g_1(x)$ with a proton target [48], together with earlier data from SLAC [49], caused considerable excitement because it significantly violated the Ellis-Jaffe sum rule (12). In a Quark-Parton Model analysis [50], the EMC result implied that the total contribution of the quarks to the proton spin is small and compatible with zero, and that the strange sea has an appreciable negative polarisation.

This result has triggered intense experimental activities in order to verify the EMC result and to extend these measurements to the neutron and the deuteron. The SMC Collaboration at CERN has recently published a first result from deep inelastic scattering of a polarised muon beam of 100 GeV on a polarised deuteron target [51]; the data cover the range $0.006 < x < 0.6$ and are shown in Fig. 18 in terms of the virtual photon-nucleon asymmetry A_1 . After a small correction for a D state admixture to the deuteron wave function, the SMC result for the sum of the first moments of $g_1(x)$ at an average $Q^2 = 4.6 \text{ GeV}^2$ is

$$\Gamma_1^p + \Gamma_1^n = 0.049 \pm 0.044(stat.) \pm 0.032(syst.),$$

whereas the Ellis-Jaffe prediction (Eqs. (12) and (13)) at this Q^2 is $\Gamma_1^p + \Gamma_1^n = 0.187 \pm 0.010$. The conclusions from this experiment are very similar to those obtained by the EMC: the Ellis-Jaffe sum rules are violated by about two standard deviations and the nucleon spin carried by quarks is small and compatible with zero.

The E-142 Collaboration at SLAC has measured deep inelastic scattering of a polarised electron beam at energies from 19 to 26 GeV on a polarised ^3He target [52]. In ^3He , the two proton spins are paired most of the time and it is therefore, for spin-dependent scattering, a good approximation of a free neutron target. These data cover the range $0.03 < x < 0.6$ and are shown in Fig. 19, also in terms of the asymmetry A_1 . The SLAC result for the first moment of $g_1^n(x)$ at an average $Q^2 = 2 \text{ GeV}^2$ is

$$\Gamma_1^n = -0.022 \pm 0.007(stat.) \pm 0.009(syst.);$$

here, the Ellis-Jaffe sum rule (13) predicts $\Gamma_1^n = -0.021 \pm 0.018$ in perfect agreement with the data.

Figure 18: The virtual photon-deuteron cross section asymmetry A_1^d as a function of x measured by SMC, at an average $Q^2 = 4.6 \text{ GeV}^2$. Only statistical errors are shown with the data points. The systematic errors are indicated by the shaded area.

Figure 19: The virtual photon-neutron cross section asymmetry A_1^n as a function of x measured by E-142, at an average $Q^2 = 2 \text{ GeV}^2$. Statistical and systematic errors are combined in quadrature.

Table 3: *Quark-Parton Model results from the EMC+SLAC, SMC and E-142 experiments. The first error is statistical, the second systematic. E-142 quotes total errors.*

	EMC + SLAC Proton	SMC Proton + Neutron	E-142 Neutron
Γ_1	$0.126 \pm 0.010 \pm 0.015$	$0.049 \pm 0.044 \pm 0.032$	-0.022 ± 0.011
$\Delta\Sigma$	$0.120 \pm 0.094 \pm 0.138$	$0.06 \pm 0.20 \pm 0.15$	0.57 ± 0.11
Δs	$-0.190 \pm 0.032 \pm 0.046$	$-0.15 \pm 0.07 \pm 0.05$	-0.01 ± 0.06

The main results of the EMC, SMC and SLAC experiments are summarised in Table 3. $\Delta\Sigma$ and Δs are results of a QPM analysis, where

$$\Delta q \equiv \int_0^1 [q^+(x) - q^-(x)] dx \quad (20)$$

is the contribution of an individual quark flavour to the nucleon spin, and

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s \quad (21)$$

is the total quark contribution to the nucleon spin.

E-142 and SMC are complementary experiments using very different techniques. The main advantage of E-142 is high luminosity thanks to an enormous beam intensity, resulting in significantly smaller errors of the measured asymmetries than in SMC. SMC covers a larger kinematic range at small x , thanks largely due to the higher beam energy, which is an advantage in evaluating the sum rules.

Test of the Bjorken Sum Rule

Both groups have combined their results with the earlier EMC and SLAC proton data for a test of the Bjorken sum rule. SMC finds

$$\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05 (stat.) \pm 0.04 (syst.)$$

in agreement with the prediction of Eq. (11) that $\Gamma_1^p - \Gamma_1^n = 0.191 \pm 0.002$ at $Q^2 = 4.6 \text{ GeV}^2$. E-142 finds

$$\Gamma_1^p - \Gamma_1^n = 0.148 \pm 0.22$$

which is almost two standard deviations below the prediction $\Gamma_1^p - \Gamma_1^n = 0.187 \pm 0.004$ at $Q^2 = 2 \text{ GeV}^2$. The experimental situation is best summarised in the $\Gamma_1^n - \Gamma_1^p$ plane which illustrates that indeed the data fail to overlap in a common area compatible with the Bjorken prediction (Fig. 20).

Before discussing these contradictory conclusions about the validity of the Bjorken sum rule in some detail, it is appropriate to compare the experimental results at the level of the measured asymmetries or structure functions. This cannot be done directly since the asymmetries are expected to be different for proton, neutron, and deuteron targets. In Fig. 21, the proton results from EMC and SLAC and the neutron results from E-142 have been combined into a virtual photon-deuteron asymmetry A_1^d which is compared to the SMC result for the deuteron. This figure shows clearly that the three data sets are mutually consistent in the x region of overlap.

Two possibilities remain to explain the discrepancies between the first moments obtained from the different data sets, namely

Figure 20: The experimental moments Γ_1^p , Γ_1^n and Γ_1^{p+n} . The hatched areas represent the experimental uncertainties. The prediction of the Bjorken sum rule is shown for $Q^2 = 5 \text{ GeV}^2$.

Figure 21: The virtual photon-deuteron asymmetry $A_1^d(x)$. The open points are the SMC results of Fig. (18). The closed points are obtained from the EMC/SLAC proton data and from the SLAC E-142 neutron data. For the latter, a correction has been applied for the probability of the deuteron to be in the D state. Only statistical errors are shown.

- problems with the extrapolation of $g_1(x)$ into the unmeasured regions at small and large x , or an underestimate of the systematic error associated with this extrapolation, or
- a significant Q^2 dependence of the first moments that needs to be taken into account before comparing results obtained at different average Q^2 .

The extrapolation of $g_1(x)$ at large x is done by assuming that $A_1 = 1$ at $x = 1$; furthermore, it is constrained by the bound $|A_1| \leq 1$. More delicate is the extrapolation at small x where g_1 is usually parametrised by a Regge type form

$$g_1(x) \propto x^{-\alpha}, \quad (22)$$

with α expected to be in the range $-0.5 < \alpha < 0$. The exact value of α and the value of x up to which this functional form is valid are not predicted by Regge theory [53, 54]. As long as theory does not give us a better prescription, only more data with improved kinematic range and smaller errors can better constrain the integral over the unmeasured region. In this context, it should be noted that the SMC results indicate a negative A_1 in a region of small x which is not covered by the E-142 data (Figs. 18 and 19).

The Q^2 dependence of the first moments has recently received much attention. Ellis and Karliner [55] have undertaken a careful reexamination of both the experimental data and the theoretical predictions from this point of view. They evolve the EMC/SLAC result on Γ_1^p obtained at an average $Q^2 = 10.7 \text{ GeV}^2$ to the lower Q^2 of the SMC and E-142 data, and re-evaluate Γ_1^n from the E-142 data using the small x extrapolation of Eq. (22). This leads to improved determinations of $\Gamma_1^p - \Gamma_1^n$ from the experimental data. On the theoretical side, they apply higher order perturbative QCD corrections to the Bjorken sum rule which have recently been computed up to $\mathcal{O}(\alpha_s^3)$ [56], target mass corrections (kinematical higher twists), and dynamical higher twist corrections [57]. Their main result is summarised in Fig. 22 which shows that there are no mutual inconsistencies between the data and the Bjorken sum rule once all Q^2 dependent corrections have been properly applied. Ellis and Karliner conclude that the Bjorken sum rule is confirmed by all experimental data at the 12% level; from a combined Quark-Parton Model analysis they find a total quark contribution to the nucleon spin of $\Delta\Sigma = 0.22 \pm 0.10$ and a strange sea contribution of $\Delta s = -0.13 \pm 0.04$. A related analysis has been made by Close and Roberts who also conclude that the Bjorken sum rule is confirmed but find a larger $\Delta\Sigma = 0.41 \pm 0.05$ [58].

In conclusion, there is no evidence for a violation of the Bjorken sum rule, and great care should be exercised in analysing the data before rocking one of the cornerstones of the Quark-Parton Model. More data are urgently awaited for a better understanding of the experimental situation. New results for the proton are expected soon from SMC and from SLAC experiment E-143; more data from proton, ^3He and deuteron targets are to be expected from SMC, SLAC and from the HERMES experiment at HERA over the next few years.

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Figure 22: Test of the Bjorken sum rule due to Ellis and Karliner. The data points are the re-evaluated results from E-142 (left) and SMC (right). The upper band (dash-dotted lines) is the Bjorken prediction including perturbative corrections up to order $\mathcal{O}(\alpha_s^3)$; the lower band (solid lines) includes, in addition, kinematical and dynamical higher twist corrections.

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