# The EMC effect



2003 Rep. Prog. Phys. 66 1253

(http://iopscience.iop.org/0034-4885/66/8/201)

INSTITUTE OF PHYSICS PUBLISHING REPORTS ON PROGRESS IN PHYSICS

Rep. Prog. Phys. **66** (2003) 1253–1297 PII: S0034-4885(03)07791-1

# The EMC effect

**P R Norton**

CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

E-mail: P.R.Norton@rl.ac.uk

Received 1 November 2002, in final form 28 April 2003
Published 2 July 2003
Online at stacks.iop.org/RoPP/66/1253

## Abstract

The status of the EMC effect, the anomalous scattering of leptons on nuclei, is reviewed, together with models which have been formulated to explain it. The implications for other processes are discussed, in particular the relevance to problems in conventional nuclear physics.

0034-4885/03/081253+45$90.00  

## 1. Introduction

The scattering of charged leptons, both electrons and muons, has long proved to be one of the most powerful tools in nuclear and particle physics. Leptons are pointlike objects which interact with the target via the electromagnetic force, the exchange of photons. The pointlike probe and the well-understood force mean that the structure of the target can be deduced from the measured differential scattering cross-section. In turn, details of the structure of atoms, nuclei and nucleons have been revealed as the resolving power of the probe improved by increasing the lepton energy. The quark structure of matter was given credence by a series of pioneering electron scattering experiments in the late 1960s and early 1970s, and by neutrino scattering experiments in the 1970s. The scattering from a proton appears as the scattering from pointlike objects within it, the quarks. Experiments with muon and neutrino beams at higher energies have increased further our understanding of quarks and the forces between them, extended further by electron and positron scattering from protons in the HERA collider.

Nuclei consist of protons and neutrons bound together by the strong nuclear force with a binding energy small compared with the nucleon mass. It was therefore expected that the cross-section for muon scattering on nuclei would be the sum of the cross-sections on the number of nucleon constituents of the target. It therefore came as a complete surprise when this was found not to be the case: the cross-sections measured on iron and deuterium, a loosely bound state of a proton and a neutron, were different (Aubert *et al* 1983b). This has come to be known as 'the EMC effect'.

This review summarizes the current experimental status of the effect, both the original discovery and recent work after many years of sustained study, and the theoretical and phenomenological developments which have followed. The impact of the discovery was large, leading to new lines of experiment in particle and nuclear physics, and new thinking in nuclear physics and the role of quarks in nuclei, as well as more careful studies of conventional nuclear physics descriptions. One paper has seldom had such an effect.

The review is laid out as follows: section 2 reviews the phenomenology of deep inelastic scattering; section 3 summarizes the discovery of the effect and its immediate aftermath; further measurements are discussed in section 4 and models in section 5; other relevant processes are shown in section 6, and relevance for nuclear physics in section 7; a final summing-up is given in section 8. Other recent reviews have laid more emphasis on conventional nuclear models (Bickerstaff and Thomas 1989), on models of shadowing (Arneodo 1994, Piller and Weise 2000), and on theoretical formalism (Geesaman *et al* 1995). This review brings the experimental data up to date and puts more emphasis on the relations between the EMC effect and nuclear physics.

## 2. Phenomenology of deep inelastic scattering

A short account is given here to explain the notation used in deep inelastic scattering. More detail can be found in standard texts (e.g. Close 79). Deep inelastic scattering is conventionally described by the diagram of figure 1. Because the electromagnetic coupling constant $\alpha$ is small, it is only necessary to consider just the one-photon exchange diagram. Searches for two-photon exchange have so far proved negative, and the effects of including $Z^0$ exchange can be entirely neglected for the data in this review.

The lepton scatters from the target and imparts it a four-momentum $q^2$ given by

$$-q^2 = Q^2 = 2EE'(1 - \cos\theta) \tag{2.1}$$

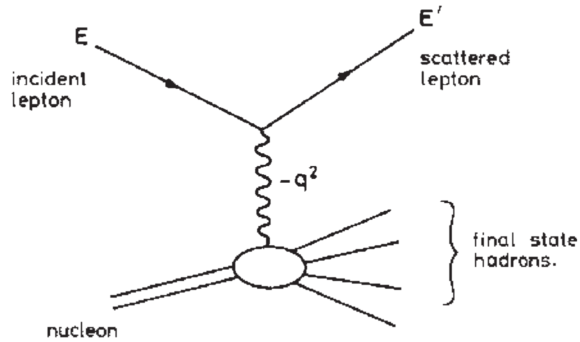


**Figure 1.** The one-photon exchange diagram for leptoproduction.

where $E$, $E'$ are the incoming and scattered lepton energies, and $\theta$ is the angle through which the lepton scattered. Lepton masses have been neglected. The differential cross-section in the laboratory frame for a muon scattering from an unpolarized proton target can be differential with respect to any two independent kinematic variables, such as $E'$ and $\cos\theta$, but it will be more transparent in what follows to use the variables $Q^2$ and $x$, the Bjorken variable defined as $x = Q^2/2M\nu$, where $M$ is the proton mass and $\nu$ is $E - E'$. The expression is:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\,\mathrm{d}x} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{Mxy}{2E}\right)\frac{F_2(x, Q^2)}{x} + y^2 F_1(x, Q^2)\right] \tag{2.2}$$

Here $y$ is the fractional energy transfer to the target, $\nu/E$. The cross-section is thus expressed in terms of two structure functions $F_1$ and $F_2$ which are characteristic of the target. Two structure functions are necessary since the virtual photon can be polarized both transversely and longitudinally: they can be separated only by making measurements of the differential cross-section at more than one beam energy, thus changing $y$ while keeping $x$ and $Q^2$ fixed. It is conventional to express the relationship between $F_1$ and $F_2$ in terms of another function

$$R(x, Q^2) = \frac{F_2}{2xF_1}\left(1 + 4\frac{M^2x^2}{Q^2}\right) - 1 \tag{2.3}$$

where $R$ is the ratio of the absorption cross-sections for longitudinal and transverse virtual photons.

Measurements of the structure functions at SLAC (Bloom *et al* 1969) revealed that they were essentially independent of $Q^2$ at fixed $x$, as would be the case for scattering from pointlike structureless objects within the proton known as partons (Feynman 1972). The identification of partons with quarks was made evident from neutrino data (Deden *et al* 1975), giving rise to the quark–parton model.

The structure function $F_2$ is given by the sum over the scattering from the quarks in the target:

$$F_2(x) = \sum_i e_i^2 (xq_i(x) + x\bar{q}_i(x)) \tag{2.4}$$

where the sum is over all quark flavours in the target $(u, d, s, c, \ldots)$. $e_i^2 (= (\frac{2}{3})^2$ for $u, c$; $(\frac{1}{3})^2$ for $d, s)$ represents the square of the electric charge of the quark, and $q(x)$ and $\bar{q}(x)$ represent the quark and antiquark distribution functions, the probability that the quark (or antiquark) carries a fraction $x$ of the proton's momentum in a Lorentz frame in which the proton is moving very fast (the infinite-momentum frame, see Feynman (1972)). Since quarks have spin $\frac{1}{2}$, $R$ is expected to be small, and zero in the limit of zero quark transverse momentum, since by helicity conservation in electromagnetic interactions, a spin $\frac{1}{2}$ quark cannot absorb a photon of helicity zero. This is indeed confirmed by measurements of $R$, which is small, particularly at high $Q^2$ (e.g. Benvenuti *et al* (1989)). At energies above the threshold for charmed quark production, the structure function can be written as

$$F_2(x) = \tfrac{4}{9}(xu(x) + x\bar{u}(x)) + \tfrac{1}{9}(xd(x) + x\bar{d}(x)) + \tfrac{1}{9}(xs(x) + x\bar{s}(x)) + \tfrac{4}{9}(xc(x) + x\bar{c}(x)) \tag{2.5}$$

Here $u(x)$, $d(x)$, $s(x)$ and $c(x)$ are the quark distribution functions for $u$, $d$, $s$ and $c$ quarks, with the bar corresponding to their antiquarks (heavier quarks ($b$, $\bar{b}$) are ignored here). Isospin invariance then relates the distributions in the neutron and proton: the $u$ quark distribution in the proton is the same as that of the $d$ quark in the neutron and vice versa. Thus the neutron structure function can be written as

$$F_2(x) = \tfrac{1}{9}(xu(x) + x\bar{u}(x)) + \tfrac{4}{9}(xd(x) + x\bar{d}(x)) + \tfrac{1}{9}(xs(x) + x\bar{s}(x)) + \tfrac{4}{9}(xc(x) + x\bar{c}(x)) \tag{2.6}$$

where $u$ and $d$ are the distributions in the proton. We can now write the structure function of an average nucleon as the average of proton and neutron

$$\begin{aligned} F_2^N(x) = {} & \tfrac{5}{18}(x(u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + s(x) + \bar{s}(x) + c(x) + \bar{c}(x))) \\ & + \tfrac{1}{6}(x(c(x) + \bar{c}(x)) - x(s(x) + \bar{s}(x))) \end{aligned} \tag{2.7}$$

The proton consists of three valence quarks ($u_\mathrm{v}u_\mathrm{v}d_\mathrm{v}$) which ensure the net charge and baryon number of the proton, together with a 'sea' of quark–antiquark pairs ($u_\mathrm{s}$, $\bar{u}_\mathrm{s}$, etc). Thus $u(x) = u_\mathrm{v}(x) + u_\mathrm{s}(x)$. The experimentally determined valence and sea distributions will be discussed later in this section.

Nucleon structure may also be studied by neutrino scattering. The cross-section for neutrino (antineutrino) scattering on a nucleon by the weak charged current interaction is

$$\frac{\mathrm{d}^2\sigma^{\overset{(-)}{\nu}}}{\mathrm{d}x\,\mathrm{d}y} = \frac{G_\mathrm{F}^2 ME}{\pi}\left[\left(1 - y - \frac{Mxy}{2E}\right)F_2 + xy^2F_1 \pm \left(y - \frac{y^2}{2}\right)xF_3\right] \tag{2.8}$$

where $G_\mathrm{F}$ is the Fermi coupling constant and the other variables have the same significance as for muon scattering. The extra term in $xF_3$ arises from the parity violation in the weak interaction, and represents the difference between scattering by $\nu$ and $\bar{\nu}$. The particular value of neutrino and antineutrino scattering is that the valence and sea contributions to the quark distribution functions may be separated. For an isoscalar target

$$\frac{\mathrm{d}^2\sigma^{\nu N}}{\mathrm{d}x\,\mathrm{d}y} = \frac{G_\mathrm{F}^2 ME}{\pi}\left[xq(x) + (1-y)^2x\bar{q}(x) + (1-y)xq_\mathrm{L}(x)\right] \tag{2.9}$$

$$\frac{\mathrm{d}^2\sigma^{\bar{\nu}N}}{\mathrm{d}x\,\mathrm{d}y} = \frac{G_\mathrm{F}^2 ME}{\pi}[x\bar{q}(x) + (1-y)^2xq(x) + (1-y)xq_\mathrm{L}(x)] \tag{2.10}$$

$q_\mathrm{L}$ is the distribution for longitudinal scattering on quarks, which is small and can be neglected for our present purposes. Thus the $q(x)$ and $\bar{q}(x)$ distributions can be separated by studying the $y$-dependence of $\nu$ and $\bar{\nu}$ scattering.

Since $x$ represents the fractional momentum carried by quarks or antiquarks in the infinite-momentum frame, the total momentum carried by quarks and antiquarks is

$$\int_0^1 F_2^{\nu N}\,\mathrm{d}x \simeq \frac{18}{5}\int_0^1 F_2^{\mu N}\,\mathrm{d}x = \int_0^1 x\,\mathrm{d}x(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c}) \tag{2.11}$$

This is measured to be around 45–50%. The remainder of the momentum is carried by gluons, the neutral carriers of the forces between quarks, which do not feel the electromagnetic

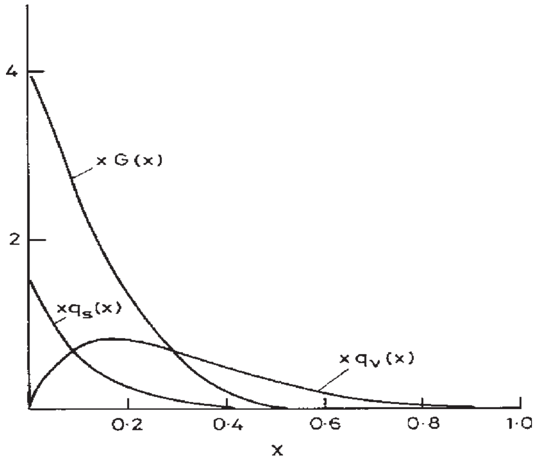


**Figure 2.** Schematic illustration of the $x$ dependence of the valence quark, sea quark and gluon distribution in the proton.

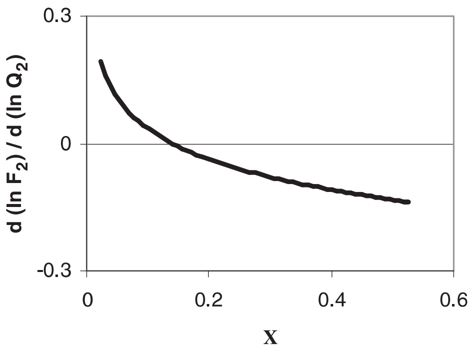


**Figure 3.** The evolution of $F_2(D)$ with $Q^2$.

coupling. Approximate and schematic $x$ distributions for valence quarks $(q - \bar{q})$, sea quarks $(2\bar{q})$ and gluons are shown in figure 2.

Deep inelastic scattering (i.e. at high values of $\nu$ and $Q^2$) of electrons, muons and neutrinos has proved one of the most useful experimental tools for revealing details of the strong interaction between quarks and gluons, and has underpinned the non-Abelian gauge theory known as quantum chromodynamics (QCD). As $Q^2$ increases, the structure functions change in a characteristic way: as the resolving power of the probe is improved, the quarks and gluons are revealed as splitting and sharing their momenta (quarks radiate gluons, gluons dissociate into $q\bar{q}$ pairs and into more gluons), and the distributions are observed to shrink to lower values of $x$. The evolution of $F_2$ with $Q^2$ is shown in figure 3. $F_2$ grows with $Q^2$ at small $x$ and reduces at large $x$. For valence quarks, this change with $Q^2$ is given by (Altarelli and Parisi 1977):

$$\frac{\mathrm{d}F_2^v(x)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s}{4\pi}\int_x^1 P_{xy}F_2^v\left(\frac{x}{y}\right)\mathrm{d}y \tag{2.12}$$

where $\alpha_s$ is the strong coupling constant and $P_{xy}$ is a 'splitting function' defined in QCD which determines how the quark's momentum is degraded by gluon emissions. More details may be found in standard texts (e.g. Leader and Predazzi (1996)).

## 3. The discovery of the effect

As part of a comprehensive study of muon scattering, the European Muon Collaboration measured structure functions on hydrogen, deuterium and iron targets. The purpose of using iron was to increase the experimental luminosity, providing more precise measurement of structure functions at high $Q^2$ and allowing the study of rarer processes such as charm production.

When the iron and deuterium structure functions $F_2$ per nucleon were compared, the ratio of the cross-sections was not unity (Aubert *et al* 1983b). The ratios depended upon $x$, although at fixed $x$ there was no evidence for a $Q^2$ dependence. Hence the ratios were averaged over $Q^2$, and showed the dependence on $x$ depicted in figure 4, which is very slightly different from the original publication. The range of $Q^2$ varied with $x$: $8 < Q^2 < 20\,\mathrm{GeV}^2$ for $x = 0.05$–$35 < Q^2 < 200\,\mathrm{GeV}^2$ for $x = 0.65$. There are many points to be made concerning the experimental ratios:

(i) There was an overall normalization uncertainty of 7% in the ratio $F_2^{\mathrm{Fe}}/F_2^{\mathrm{D}}$.
(ii) The error bars show an inner bar of statistical errors, and an outer bar representing all the estimated systematic errors combined in quadrature.
(iii) The iron data were corrected for the neutron excess in iron using the ratio $F_2^n/F_2^p$ measured by EMC (Aubert *et al* 1983a). The correction was negligible at small $x$ and amounted to only 2.3% at $x$=0.65.
(iv) No attempt was made to correct the iron or deuterium data for Fermi motion of the nucleons in the nucleus. The effect is not expected to cancel because of the larger Fermi momentum in iron, but predictions for the correction (Bodek and Ritchie 1981), as shown by the solid line in figure 4, clearly do not explain the difference.
(v) It was assumed in evaluating $F_2$ that $R$ was zero. This was consistent with the measurements made by EMC on iron (Aubert *et al* 1986) and hydrogen (Aubert *et al*

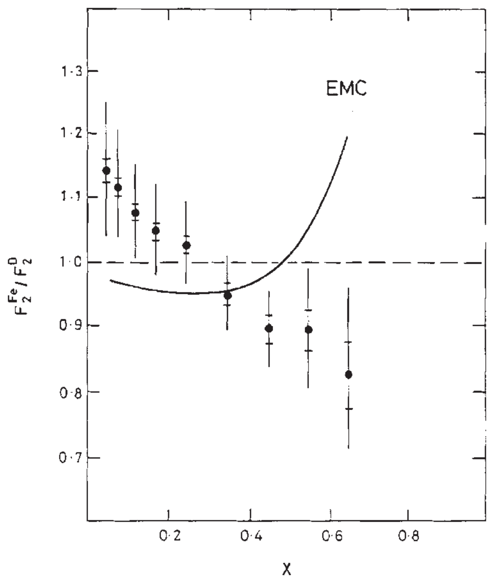


**Figure 4.** The final published EMC measurement of the structure function ratio (from Aubert *et al* (1987)), which differs slightly from the original data (Aubert *et al* 1983b) chiefly in a normalization change of around 3% (reproduced with permission from Elsevier).

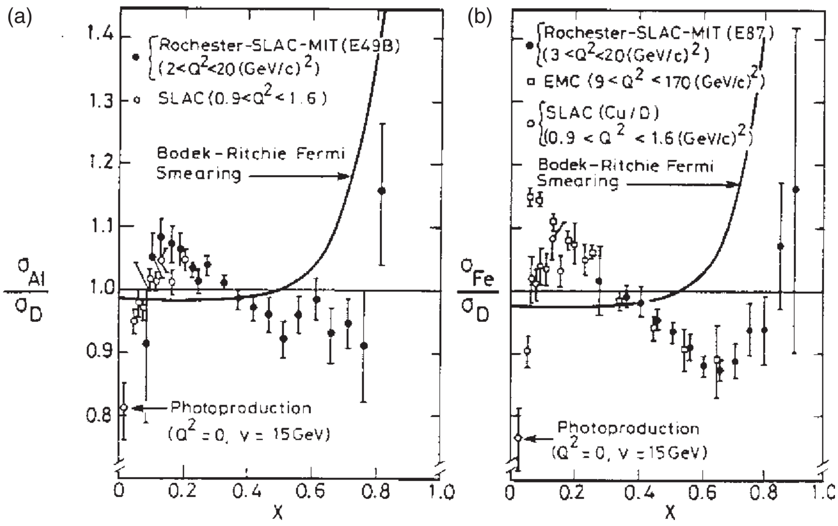


**Figure 5.** The original SLAC measurement retrieved from empty target data from earlier experiments (from Bodek *et al* (1983b)).

1985). Indeed, more strictly, it was assumed that $R$ was the same for iron and deuterium, although it should be noted that $F_2$ is largely insensitive to $R$.

The EMC did not set out to measure the iron-to-deuterium ratio with high precision, since any such anomaly was entirely unexpected. The data were taken under different running conditions and at different times, and the systematic errors in the ratio were consequently large. Despite this, the errors were felt to be sufficiently well-understood to claim this as a new effect.

Confirmation of the anomalous result was not long in coming. The empty target data from old SLAC-MIT experiments on electron–deuteron scattering were retrieved and analysed by a Rochester-SLAC-MIT group (Bodek *et al* 1983a, b) with the results shown in figure 5 for iron and aluminium compared with deuterium. The EMC results were confirmed for $x \gtrsim 0.2$, but at lower $x$ the SLAC-MIT experiment had no data. Another SLAC experiment (Stein *et al* 1975) with data at lower $x$ had observed a rise in the ratio above unity at $x = 0.1$ followed by a turnover to below unity at still lower $x$, but these data were at low $Q^2$ where nuclear shadowing might be expected to play a role. At very high $x$ the SLAC-MIT ratios show a sharp rise above unity, indicating that the effects of Fermi motion in the heavy target at last take over.

In the context of the parton model, these data imply a change in the structure function $F_2$ per nucleon in the heavy nucleus compared with deuterium. The mean value of $x$ is lower in iron, although the total momentum carried by quarks and antiquarks, given by $\int_0^1 F_2(x)\,\mathrm{d}x$ show no change within the normalization error between the data sets. The increase in the ratio of $F_2$ at small $x$ led to the general conclusion (Jaffe 1983) that the data strongly suggested an enhancement of the sea in iron.

Models to explain the effect were produced in profusion. We defer detailed discussion of these until section 5, but they fall into four broad classes: (i) An enhanced presence of pions (and possibly $\Delta$ resonances). The extra constituents carry some of the momentum away from the nucleons, but with a softer $x$ distribution. (ii) A different treatment of nucleons bound in a nucleus, using conventional nuclear physics without quarks. (iii) A change in the fundamental length scale of the nucleon, whether by an increase in the physical size of the nucleon in a nucleus or by a larger quark confinement size. (iv) Quark deconfinement: in its more modest form, the enhanced presence of six-quark bags or other quark clusters within the nucleus; in a more radical form quarks are completely deconfined and free to roam all over the nucleus.

It was therefore necessary to embark on a detailed programme of deep inelastic scattering on many nuclei to study the $A$-dependence, the $Q^2$ dependence and the relative contribution of sea and valence quarks to the effect. These will be described in the following section.

## 4. Further deep inelastic scattering measurements

Many groups began studies of the outstanding experimental questions listed above. These are discussed here classified by groups or experimental facilities rather than in strict chronological order, and include data published up to the year 2002.

### *4.1. Electron experiments at SLAC*

A dedicated experiment was undertaken at SLAC to explore the EMC effect over a wide range of nuclei from $^4$He to $^{197}$Au using electron beams of energy between 8 and 24.5 GeV (Arnold *et al* (1984), with an updated version in Gomez *et al* (1994)). The latter results are shown in figure 6, where the cross-section ratios $\sigma_A/\sigma_D$ are plotted against $x$ for each nucleus. The main features of the data are:

(i) For large $x \gtrsim 0.3$ the EMC results were confirmed.
(ii) In contrast to the EMC data, little if any rise is seen in the ratio at small $x$, although the updated points exceed unity at around $x$ of 0.1 and are higher than the original data of Arnold *et al* (1984).
(iii) The $A$-dependence of the effect is approximately logarithmic in $A$, but in the variation from nucleus to nucleus, the nuclear density plays an important part. For example, $^4$He shows a larger effect, and $^9$Be a smaller effect, than the simple ln $A$ behaviour.
(iv) No significant $Q^2$-dependence is seen on iron between these data and EMC.
(v) For all nuclei the ratio is a minimum at $x \sim 0.65$; at higher $x$ the rapid rise is presumably ascribable to Fermi motion.

The structure functions $F_1$ and $F_2$ were not separated at all data points, hence the plot of cross-section ratios in figure 6. Provided that $R$ does not depend on $A$, this is equivalent to ratios of $F_2$. Where the separation was possible, there was initially a hint of an $A$-dependence of $R$, but with rather large errors. A further experiment E140 (Dasu *et al* 1988, 1994) found that the value of $R_{\mathrm{Fe}} - R_{\mathrm{D}}$, averaged over the range $0.2 \leqslant x \leqslant 0.5$ and $1 \leqslant Q^2 \leqslant 5\,(\mathrm{GeV\,c^{-2}})$ was $0.001 \pm 0.018$ (stat) $\pm 0.016$ (syst). This result (E140) came from a run with greater statistical precision than earlier ones. Although $R$ is clearly not dependent on $A$ in this kinematic range, at lower values of $x$ interesting things may happen. $R$ gets a contribution from the $p_{\mathrm{T}}$ generated by gluons splitting into $q\bar{q}$ pairs, and differences in the gluon distribution in nuclei may be reflected in $R$. This latter run used better radiative corrections than those employed previously (technically, the 'complete formalism' rather than the energy-peaking approximation). This brought the SLAC data (Gomez *et al* 1994) more into line with EMC, the SLAC data for the structure function ratio now above unity for $x$ between 0.1 and 0.2. These corrections were applied in a uniform way to the earlier data (Stein *et al* 1979) by Rock and Bosted (2001), and the outcome shown in figure 6 is a remarkably consistent set of data from the SLAC experiments. Nevertheless, great care has to be taken with radiative corrections at very low $x$, where radiative tails from both coherent nuclear elastic scattering and incoherent quasielastic

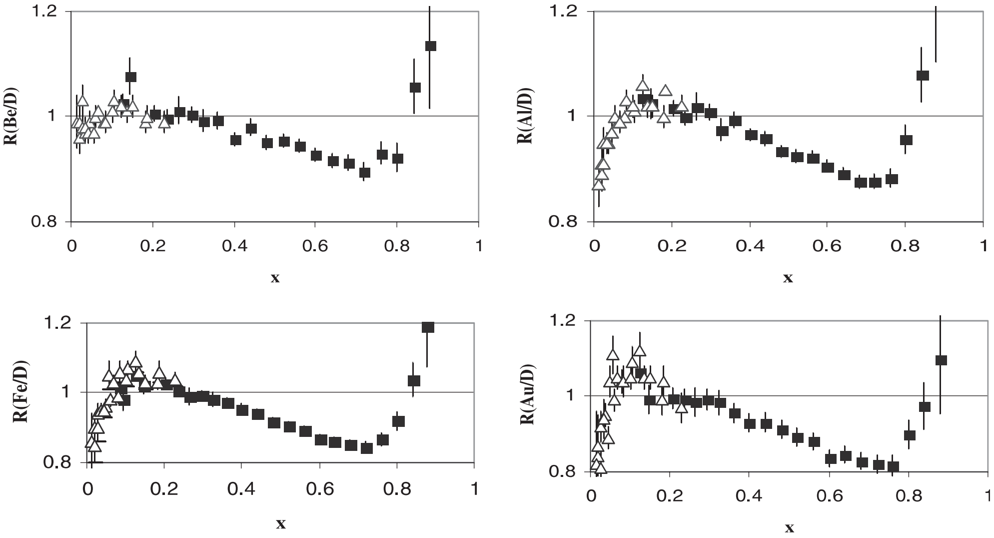


**Figure 6.** Cross-section ratios compared with deuterium for SLAC data from Gomez *et al* (1994) (■) and Stein *et al* (1975) updated by Rock and Bosted (2001) (△) for Be, Al, Fe and Au. Data were also taken on He, C, Ca and Ag by Gomez *et al*.

scattering have to be subtracted, and the effect of Pauli blocking on the quasielastic tail taken into account.

### *4.2. Neutrino measurements*

Results from many neutrino experiments have been reported. Comparison of structure functions between heavy nuclei and deuterium or hydrogen all suffer from large statistical uncertainties because of low event-rates on light targets. Results have been obtained from the CDHS experiment (Abramowicz *et al* 1984), the BEBC-TST experiment (Parker *et al* 1984), the BEBC experiments WA25 and WA59 (Cooper *et al* 1984, Guy *et al* 1987) and the 15 ft bubble chamber at Fermilab (Ammosov *et al* 1984, Hanlon *et al* 1985). The bubble chamber experiments compared hydrogen or deuterium with neon. While detailed comparisons with electron and muon data are made difficult because of the limited statistics, the trends are of an 'EMC ratio' somewhat below unity for $x < 0.1$ (in contradiction with the original EMC result of Aubert *et al* (1983b)), a rise above unity for $0.1 < x < 0.3$ and a steady fall beyond. The data are at considerably lower $Q^2$ than EMC, and any differences could conceivably be attributed to a $Q^2$-dependence of the effect. Nevertheless, there is no $Q^2$-dependence visible in the neutrino data on ratios of structure functions between neon on the one hand and hydrogen or deuterium on the other.

As mentioned in section 2, the chief value of neutrino data is in the separation of sea and valence contributions to the structure functions. The sea enhancement in Fe over H, integrated over all $x$, found by CDHS (Abramowicz *et al* 1984) was $1.10 \pm 0.11(\text{stat}) \pm 0.07(\text{syst})$. Little conclusion can be drawn because of the large errors, but it is clear that a large sea enhancement is not favoured. The BEBC experiment has attempted to parametrize the sea distribution as a function of $x$. The ratio on the sea distribution of neon and deuterium is found to be $0.92 \pm 0.05$, assuming $R_{\text{Ne}} = R_{\text{D}}$ and no change in shape of the sea, and $0.88 \pm 0.07$ if only the former is assumed (Guy *et al* 1987). The absence of an enhancement of the sea is independent of the $Q^2$-cut made on the data, thus eliminating $Q^2$-dependent shadowing as the reason for any discrepancy. One concludes that a strong enhancement of the sea in nuclei can be ruled out by the neutrino data.

The use of a bubble chamber as the experimental target offers the opportunity of further insights into the EMC effect. For example, interactions on neutrons and protons might be separated by measuring the net charge of the hadronic final state '$X$' ($\bar{\nu}p \rightarrow \mu^+X^0$, $\bar{\nu}n \rightarrow \mu^+X^-$). The result of comparing deuterium data from CERN with neon data from FNAL (Asratyan *et al* 1985, 1986) suggests that for $x > 0.3$ the ratio $\sigma_n/\sigma_p$ is smaller in neon than in deuterium, i.e. the EMC effect is bigger for neutrons than protons. The magnitude of the effect is somewhat surprising, and the systematic errors associated with the technique are difficult to assess, given that the data comes from a comparison of two completely different experiments. Further studies with better control of systematics would be interesting.

Another technique (Kitagaki *et al* 1988) is to try to separate interactions on deeply-bound nucleons from those near the surface. The presence of 'dark tracks' is assumed to identify an interaction on a nucleon which has strong correlation with its neighbours which would occur if it was deeply bound (see also Ishii *et al* (1989)).The EMC effect is claimed to be small for events with no dark tracks (quasifree nucleons) and large when they are present. As we shall see later, this trend would be expected in most models of the EMC effect (Kumano and Close 1990). However, this experimental result is not supported by a study of BEBC data (Guy *et al* 1989), and is claimed by others (Melnitchouk *et al* 1992) to be the result of an inherent fragmentation bias.

### *4.3. Results from the BCDMS experiment at CERN*

The BCDMS experiment at CERN was a large spectrometer of iron toroids and was used to compare structure functions on deuterium with those on nitrogen (Bari *et al* 1985) and on iron (Benvenuti *et al* 1987). The results are shown in figure 7. The main features are: for the iron, consistency between BCDMS and EMC for $x \geqslant 0.3$, up to a normalization discrepancy of 3%, largely removed by a subsequent renormalization of the EMC data (Aubert *et al* 1987). At smaller $x$ the data lie between the continuously rising trend of the original EMC data and the very flat behaviour of the original SLAC data, although they compare well with old SLAC data on copper at very low $Q^2$ (Stein *et al* 1975) and changes to SLAC data and new EMC data bring better agreement.

Although no significant $Q^2$ dependence is seen in the data, or between BCDMS and SLAC at high $x$, it is difficult to be conclusive about this. The full $Q^2$ range of BCDMS is covered by exposures at different beam energies. Any suggestion of a $Q^2$ dependence seen needs better data to be convincing. The nitrogen data are consistent with the SLAC carbon data, but are less

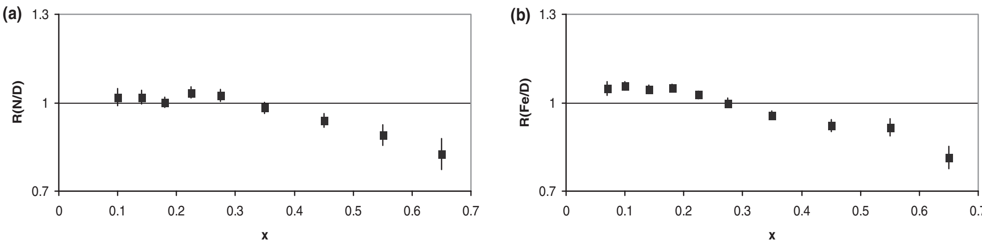


**Figure 7.** BCDMS data on structure function ratios for (*a*) nitrogen (Bari *et al* 1985) and (*b*) iron (Benvenuti *et al* 1987).

precise and seem to have a large slope in $x$; the $A$-dependence in the BCDMS data between nitrogen and iron is not clearly demonstrated, in contrast to what was observed at SLAC.

### 4.4. Further results from EMC

The EMC performed three further experiments to check different aspects of the original results, the second of which was proposed before the announcement.

*4.4.1.* The first of these further experiments was an attempt to reduce the systematic errors in the structure function ratios. Thin targets of different materials were successively introduced into the beam and changed at regular intervals (Ashman *et al* 1988). The results for carbon, copper and tin compared with deuterium are shown in figure 8 and also include further data taken with copper and deuterium described in section 4.4.3. The thin targets resulted in somewhat inferior statistical precision, but the results compare well with the old EMC data only for $x \geqslant 0.08$. The trend of the new data is clearly different and the ratio no longer continues to rise as $x$ tends to zero; indeed it turns over to a value below unity at $x \lesssim 0.1$. The integral of $F_2$ between $x = 0.02$ and 0.7 is the same within errors for copper and deuterium. The new data show no requirement for an enhancement of the sea at low $x$ and suggest that the original data must have been subject to greater systematic errors than previously estimated. It is just in this region that there is a discrepancy between $F_2$ measured on hydrogen and deuterium between EMC and BCDMS (Benvenuti *et al* 1989).

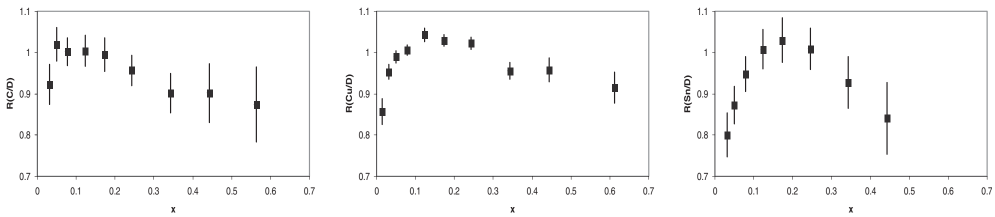


**Figure 8.** Cross-section ratios compared with deuterium for EMC data on C, Cu and Sn (Ashman *et al* 1988, 1993).

*4.4.2.* In a further and separate experiment, also known as NA28, the EMC introduced a new trigger and muon detection system at small scattering angles (down to 2 mrad) to study $\sigma_A/\sigma_D$ at low $x$ and $Q^2$ to study the possible onset of nuclear shadowing. Targets of carbon and calcium were compared with deuterium (Arneodo *et al* 1988, 1990). The results are most remarkable (figure 9); the ratios do indeed show evidence of shadowing at very small $x$ ($\sigma_A/\sigma_D < 1$), but with no dependence on $Q^2$. This is in contrast with the shadowing in the vector dominance model in which a $1/Q^2$ dependence is expected. The data also link up well with other data at higher $x$ (Ashman *et al* 1988, Bari *et al* 1985, Benvenuti *et al* 1987, Stein *et al* 1975), with a Fermilab muon experiment (Goodman *et al* 1981), and with photoproduction (Caldwell *et al* 1979). The same characteristic behaviour was seen in earlier less precise electroproduction experiments (e.g. Bailey *et al* (1979)). Some of these experiments had small angular acceptance; $x$ and $Q^2$ were highly correlated and it was hard to disentangle $Q^2$ dependence from $x$ dependence.

*4.4.3.* The final data taken by EMC in connection with the effect was a direct comparison of copper and deuterium, using two 1 m deuterium targets alternated with three targets of Cu

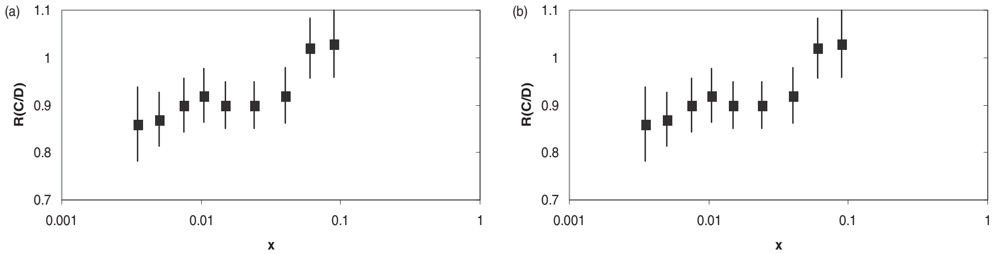


**Figure 9.** Cross-section ratios compared with deuterium for EMC NA28 data on (*a*) C and (*b*) Ca (Arneodo *et al* 1988, 1990).

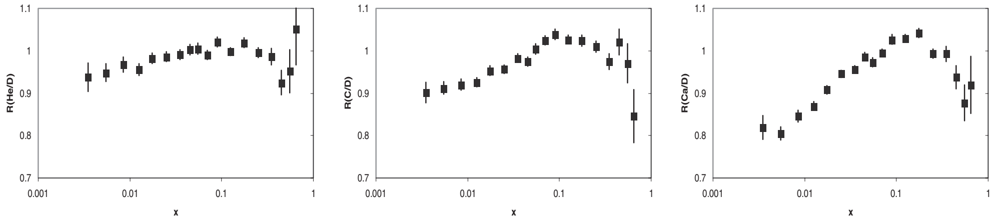


**Figure 10.** Cross-section ratios compared with deuterium for NMC data on He, C and Ca (Amaudruz *et al* 1995).

(Ashman *et al* 1993). The results confirmed those shown in section 4.4.1 and are of higher precision. The data for Cu from both experiments have been combined and are shown in figure 8.

### 4.5. Results from NMC

The new muon collaboration (NMC) continued the study of the EMC effect at CERN, measuring EMC ratios on the nuclei He, Li, C and Ca (Amaudruz *et al* 1991, 1992a) with high precision, particularly at small values of $x$. The shadowing seen by EMC was confirmed, and the $Q^2$-dependence is extremely weak. The measurements on $^{6}$Li, $^{12}$C and $^{40}$Ca (Amaudruz *et al* 1992a) were specifically to study the dependence on nuclear size and density. $^{6}$Li and $^{12}$C have approximately equal sizes but different densities; $^{40}$Ca is bigger than $^{12}$C but of a comparable density. The results show that both factors are at work at small $x$: $^{12}$C is suppressed relative to $^{6}$Li (density effect) whereas the suppression in $^{40}$Ca is twice as large (density and size). The data were subsequently revised (Amaudruz *et al* 1995) to correct for an error in the mass of the deuterium target and to introduce new radiative corrections based on more recent structure function data on deuterium and on new improved calculations (figure 10). The effect of the changes was in general to increase the EMC ratio of up to 2.5% for calcium at the lowest values of $x$.

In a further measurement (Amaudruz *et al* 1992b) the same collaboration has compared $R$ for different targets in the $x$ region between 0.01 and 0.3. The difference $\Delta R = R^{\mathrm{Ca}} - R^{\mathrm{C}}$ is $0.027 \pm 0.026$ (stat) $\pm$ 0.020 (syst), compatible with zero, and could be used to set limits on the difference of the gluon distribution between the two nuclei. Subsequent measurements (Arneodo *et al* 1995) were reported at very small $x$ using a different method of radiative corrections in which the final state radiated photon was vetoed. This method will be discussed in the next section; radiative corrections at very small $x$ are substantial and in addition there is an experimental contribution from $\mu$-electron scattering which has to be eliminated by acceptance cuts. Finally, NMC carried out a high statistics study using solid targets only (Be, C, Al, Ca, Fe, Sn and Pb) to investigate the detailed $x$ and $Q^2$ variation of the effect (Arneodo *et al* 1996a, b). Both variations confirm previous conclusions in that there is no significant variation with $Q^2$ for $x$ above 0.06 and that the variation with $A$ is approximately logarithmic.

One final comment on the NMC data is that there now seems to be agreement on the $F_2$ structure function between NMC and the neutrino experiment CCFR at Fermilab (Yang *et al* 2001a) now that the neutrino analysis is done in a model-independent way at low $x$, using a physics model-independent two parameter fit to $F_2$ and $xF_3$. Previous analyses (Seligman *et al* 1997) had used a model (the 'slow rescaling model') which attempted to take into account the difference in scattering on $c$ and $s$ quarks between neurtino and muon scattering. In neutrino scattering on $s$ quarks there is a threshold suppression arising from the production of heavy $c$ quarks in the final state. In muon scattering there is no such suppression in scattering on $s$ quarks, but there is on $c$ quarks since two heavy quarks appear in the final state. This model was too naive and produced a 15% discrepancy between muon and neutrino data at $x = 0.0125$.

## 4.6. The Fermilab E665 experiment

The ratio of cross-sections in muon scattering on Xe, and other nuclei, and D has been measured by the E665 collaboration (Adams *et al* 1992a, b, 1995) in the Fermilab muon beam. The higher energy of the beam, compared with CERN, allows a study of a lower region of $x$ than had been possible before. The result (figure 11) shows the now familiar pattern of $x$-dependent shadowing, but below $x = 0.003$ the ratio flattens at around 0.7 down to $x = 2 \times 10^{-5}$ (or, as they put it, 'saturates'). The interpolated photoproduction ratio is $0.6 \pm 0.3$. Subsequent ratios of cross-section ratios of C, Ca and Pb to D have been presented (Adams *et al* 1995) in which two sets of radiative corrections were calculated and which cannot be said to agree. E665s favoured method was to veto the radiated photon directly and to cut out the $\mu$-e scattering, but they also show the results using the FERRAD radiative correction programme as used by NMC. The agreement between E665 and NMC is not ideal, but better if they use the same radiative correction method, when E665 lie between 3% and 5% above NMC at low $x$. The use of the FERRAD program restricts the $x$ range which can be explored.

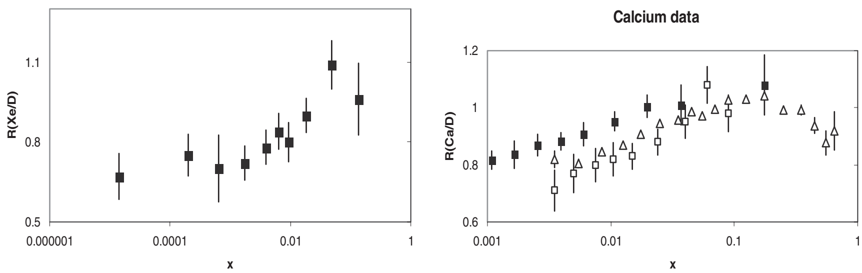


**Figure 11.** Left: shadowing data from E665 on Xe (■) Adams *et al* (1992a); right: E665 Ca data (■) Adams *et al* (1995) calculated using the veto method of radiative corrections compared with NMC (△) Amaudruz *et al* (1995) and EMC-NA28 (□) Arneodo *et al* (1990).

## 4.7. The HERMES experiment at HERA

The HERMES experiment at HERA was designed primarily to investigate the spin structure of the nucleon by colliding polarized positrons with polarized gas-jet targets. In the data relevant to the EMC effect, 27.5 GeV positrons collided with gas jets of hydrogen, deuterium, $^{3}$He and $^{14}$N. The kinematic range covered was $0.013 < x < 0.65$ and $0.5\,\mathrm{GeV\,c^{-2}} < Q^2 < 15\,\mathrm{GeV\,c^{-2}}$. The result reported (Ackerstaff *et al* 2000) was that the ratio of the cross-sections relative to deuterium for $x < 0.06$ diverged dramatically from the data of NMC (Amaudruz *et al* 1995) and E665 (Adams *et al* 1995), while agreeing with them and with SLAC (Gomez *et al* 1994) at higher $x$. This was interpreted as an $A$-dependence of $R(= \sigma_{\mathrm{L}}/\sigma_{\mathrm{T}})$ at low $x$ and low $Q^2$. Note that for a given $x$ the HERMES data were at a lower $Q^2$ than the NMC and E665 data. In each $x$ bin below $x = 0.06$ the discrepancy grew with $Q^2$, giving the appearance of a discontinuity in $Q^2$ when compared with the other experiments. Furthermore, when the data was plotted against the polarization parameter $\epsilon$ in each $x$ bin there was a pronounced dependence on $\epsilon$ at low $x$, which could be used to extract $F_2^A/F_2^{\mathrm{D}}$ and $R_A/R_{\mathrm{D}}$ separately. The $F_2$ ratio appeared to agree with a parametrization of the NMC and SLAC data, while the $R$ ratio was large (as big as 5 for $^{14}$N) at very small $x$ and fell with both $x$ and $Q^2$. As is usual in deep inelastic scattering, radiative corrections are large at small $x$. They were calculated in the conventional manner, but reached factors of 0.55, 0.46 and 0.37 multiplying the observed signal for D, $^{3}$He and $^{14}$N, respectively, in the lowest $x$ bin. It is clear they have to be treated with care, but the method used by HERMES seems to follow that of NMC. However, the latest news from HERMES (Airapetian 2002a, b) is that the original HERMES claim has been withdrawn, that there is no variation of $R$ with $A$ visible in new data, and that the old data were subject to an event reconstruction bias.

The effect apparently seen by HERMES has been checked against other SLAC data (Rock and Bosted 2001) with a lack of confirmation. Rather old data from experiment E61 (Stein *et al* 1975), which were taken at similar kinematics to HERMES (incident beam energies of 13 and 20 GeV and a scattering angle of 4°), were radiatively corrected using techniques now standard but not achievable in 1975. The data were taken on many targets, the nearest to nitrogen being aluminium, for which the cross-section ratio shows no anomalous behaviour compared with data at $Q^2$ above 1 ($\mathrm{GeV\,c^{-2}}$). Other SLAC experiments were likewise reported to show no anomaly. Most recently, there are preliminary results from Jefferson Laboratory experiment E99-118 (Dunne 2002) with an electron beam energy of 5.65 GeV and a scattering angle of 10° on carbon, copper and deuterium. These data show much less of a discrepancy with NMC data than those of HERMES, although for a given $x$ value, the JLAB data are at lower $Q^2$.

The NuTeV experiment (formerly CCFR) at Fermilab has also searched for an anomalous behaviour of $R$ in neutrino and antineutrino interactions on iron (Yang *et al* 2001b). No such large effect is seen, although the effect could anyway be different in electron and neutrino scattering.

### *4.8. Summary of the data*

After many years of diligent experimental work, a consensus has emerged on the ratio $\sigma_A/\sigma_{\mathrm{D}}$ as a function of $x$. A compendium of these results is shown in figure 12 for $x > 0.01$ for nuclei close to Fe in the periodic table. The prominent features are: at very small $x$ $R_{\mathrm{EMC}}$ is less than unity. It rises to cross $R_{\mathrm{EMC}} = 1$ at $x \sim 0.1$, then falls to a minimum at $x = 0.65$ and thereafter rises steeply. The $Q^2$ dependence is very weak at most, and the $A$-dependence approximately logarithmic for large $x$. There is no evidence that $R = \sigma_{\mathrm{L}}/\sigma_{\mathrm{T}}$ is $A$-dependent. The behaviour of $R_{\mathrm{EMC}}$ has been parametrized by Smirnov (1995, 1999) as 'universal'. The $x$ region is divided into separate regions: shadowing, antishadowing and 'EMC effect' in the form

$$R^A_{\mathrm{EMC}}(x) = x^{m_1}(1 + m_2)(1 - m_3 x) \tag{4.1}$$

and it is found that the cross-over points between neighbouring regions, found by fitting the shadowing region to the first factor above and the 'EMC' region to the third factor, are

$A$-independent, with values of $0.0615 \pm 0.0024$ and $0.278 \pm 0.008$, respectively. The third cross-over is more difficult, but a value of $0.84 \pm 0.01$ is obtained. The data used was selected to avoid known discrepancies, but the results are probably not affected by this choice.

Many attempts have been made to produce overall fits to the nuclear dependence of the structure functions, and these can be used as a convenient parametrization of the data (Eskola *et al* 1998, 1999, Hirai *et al* 2001).

## 5. Models of the EMC effect

The announcement of the EMC effect resulted in a very large number of theoretical and phenomenological papers which provided a wide and varied series of 'explanations', over a period of many years. In any review of the subject, it is not possible to describe all the contributions which have been made, and I apologize to all authors who may feel their work has been ignored or misrepresented. Nevertheless, I shall attempt to describe the wide range of models which have been proposed. I have set them out roughly in order of increasing 'novelty' although in the summary I shall try to relate them.

In assessing the usefulness of the various models, some care must be taken. The data has not always been in the agreement described in the last section and some models made fits to only subsets of the data. In addition, many of the models have parameters to be fitted to the data, and also the set of deuterium structure functions used varies considerably from model to model. Finally, nuclear effects in deuterium have been ignored in the data, but not necessarily included in models. Therefore the physical concepts of the models will be stressed as much as the detailed comparison with experiment.

### *5.1. Models based on single nucleons*

The chief evidence that nucleons are constituents of nuclei comes from quasielastic knockout reactions. The nucleons are bound to the nucleus but retain their identity: the binding is (presumably) caused by meson exchange between nucleons, but we are concerned here with the single-nucleon aspects. Treatments of binding and of Fermi motion proposed both before (Bodek and Ritchie 1981, Frankfurt and Strikman 1981) and after (Saito and Uchiyama 1985) the announcement of the EMC effect assumed that the struck nucleon was off-shell and possessed a Fermi momentum, but also assumed that the residual nucleus, comprising A-1 nucleons, was in its ground state. This seemed a plausible assumption, but in hindsight is not so reasonable. A nucleon knocked out of some arbitrary nuclear level will in general leave the residual nucleus in an excited state (e.g. Bickerstaff and Thomas (1989)). This was the position adopted by other authors, (Akulinichev *et al* (1985a–d), Birbrair *et al* (1986), Dunne and Thomas (1986a, b), Akulinichev and Shlomo (1990), see also Bickerstaff and Thomas (1987), Nakano and Rafelski (1987), Antonov *et al* (1991)), although it is interesting to note that Migdal (1987) and Migdal *et al* (1990) are strongly critical of this approach. The statement that earlier treatments put the struck nucleon on the mass shell (Akulinichev *et al* 1985a) is erroneous since the binding energy per nucleon was allowed for. In the later binding models the average nucleon has a separation energy $\langle\epsilon\rangle$ and a momentum $\vec{p}$, and the separation energy causes the Bjorken variable $x$ to be modified: the off-mass-shell nucleons have (negative) average energies $\langle\epsilon\rangle$ and momenta $\vec{p}$ correlated by

$$\langle\epsilon\rangle + \frac{\langle\vec{p}^2\rangle}{2M_\mathrm{N}} = 2\mu \tag{5.1}$$

where $\mu$ is the chemical potential (or mass defect) of $-8$ MeV per nucleon. This relation is due to Koltun (1972) and assumes a density-independent two-nucleon interaction. The $x$-variable now becomes

$$x' = \frac{Q^2}{2p' \cdot q} \tag{5.2}$$

where $p'$ is $(M+\epsilon, \vec{p})$ (ignoring the recoil of the $(A-1)$ nucleus). This results in two effects: the $x$ value is smeared by the Fermi momentum $\vec{p}$ and shifted by an amount $\langle\epsilon\rangle/M$. In the intermediate $x$ region the latter is more important and results in a rescaling of the variable $x$. Such rescaling had been previously proposed (Garcia Canal *et al* 1984, Staszel *et al* 1984) on the slightly different grounds of an effective nucleon mass $M^* < M$ and can be related in the bag model to an equivalent dimensional rescaling inverse in the nucleon bag radius in nuclei. Changes in size of the nucleon in a nucleus will be considered further in section 5.4. The behaviour of $R_{\mathrm{EMC}}$ for $x > 0.3$ can thus be described in terms of this off-shell effect. The reduction of $R_{\mathrm{EMC}}$ with increasing $x$ is explained, but the model cannot reproduce the rise in $R_{\mathrm{EMC}}$ above unity for $x \sim 0.2$. Many questions are immediately raised in this approach and will be dealt with in turn.

The first is that all the momentum of the nucleus is no longer carried by the nucleons, and hence the description is incomplete. This defect is variously ascribed to the mesonic effects responsible for the binding, or to the presence of two-nucleon correlations at small $x$ in that the 'longitudinal extent' of the virtual photon for $x < 0.2$ is greater than the average distance between nucleons and thus the photon can interact with two nucleons in violation of the single nucleon picture. This is generally acknowledged in single-nucleon models and should not be regarded as a fundamental flaw, since the addition of binding quanta such as pions is mentioned by the original authors (Akulinichev *et al* 1985b). However, any model which has only nucleon components in the Fock space wave function can show no binding effect (Miller and Smith 2002a), and this includes nucleon–nucleon correlations if the nuclear components are only nucleons.

A second objection (Dunne and Thomas 1986b) is that the effect of recoil in the deuteron has been neglected and thus the calculation of nuclear effects in iron are overestimated. Various treatments of binding do indeed calculate the deuteron correctly, but some are not so explicit.

A much more fundamental criticism has been made (Frankfurt and Strikman 1987) of the inconsistent normalization, not only in momentum (which can be conceded) but also in baryon number (which cannot) due to a modification of the flux factor in the calculation of cross-sections. The original model (Akuninichev *et al* 1985a) adopted what will become very familiar as the convolution approach. The structure function of the nucleus is the convolution of the structure function of the nucleon and the momentum distribution of nucleons in the nucleus.

$$AF_2^A(x) = \int_x^1 \mathrm{d}z\, f(z) F_2^N\left(\frac{x}{z}\right) \tag{5.3}$$

while the longitudinal momentum distribution $f(z)$ is given by the expression

$$f(z) = \int \mathrm{d}^4 p\, S(p)\delta\left(z - \left(\frac{pq}{mq_0}\right)\right) \tag{5.4}$$

with $S(p)$ the spectral function of the nucleus and $p, q$ are the four-momenta of the struck nucleon and virtual photon, $m$ is the nucleon mass and $q_0$ is the energy transfer from the virtual photon. This gives rise to a loss of nucleon longitudinal momentum: the average is

$$\langle z\rangle = \left(\frac{1}{A}\right)\int \mathrm{d}z\, zf(z) = 1 + \frac{\langle\epsilon_\lambda\rangle}{m} \tag{5.5}$$

and the tilt of the distribution is governed entirely by the mean nucleon separation energy $\langle\epsilon_\lambda\rangle$. Furthermore, the structure function can be expanded about $\langle z\rangle$ to give (with the average nucleon kinetic energy $\langle T \rangle$)

$$\left(\frac{1}{A}\right) F_2^A(x) = F_2^N(x) - \frac{x F_2^{N'}(x)(\langle\epsilon\rangle - (2/3)\langle T\rangle)}{m} + x^2 F_2^{N''}(x)\frac{\langle T\rangle}{3m} \qquad (5.6)$$

Frankfurt and Strikman (1987) point out that the normalization of the spectral function should include an extra factor $z$ in a fully relativistic theory. This modifies $\langle z \rangle$ to $1 + \langle\epsilon_\lambda\rangle/m + \frac{2}{3}\langle T\rangle/m$ and changes the second term in the expansion of the structure function to remove any dependence on $\langle T \rangle$. Thus the effect is of opposite sign and tends to cancel the effect of $\epsilon$, which has been acknowledged in later work (Birbrair *et al* (1989a, b); see also Li *et al* (1988), Jaffe (1988), Jung and Miller (1988), Ciofi degli Atti and Liuti (1989, 1991), Kulagin (1989), Dieperink and Miller (1991)). Some of the original authors (Shlomo and Vagradov 1989, Akulinichev and Shlomo 1990) defended their model and denied the need for a flux factor correction, but the broad consensus of opinion seems to favour it, despite detailed differences in the form of the flux factor (e.g. Bickerstaff and Thomas (1989)). Other treatments of relativistic Fermi motion (Morley and Schmidt 1986) come in for similar criticisms on normalization (Frankfurt and Strikman 1987). The general conclusion is that nuclear binding cannot explain all the EMC effect and other mechanisms, such as off-shell effects (Dunne and Thomas 1986a, b, Benhar *et al* 1997, Gross and Liuti 1992) are needed to supplement it.

However, there remains a further problem concerning the values of average nucleon separation energies and the $A$-dependence. Akulinichev *et al* (1985a) used the Koltun sum rule to evaluate the relevant $\langle\epsilon\rangle$ and calculated $-39$ MeV for iron. The sum rule, on the other hand, may be violated by density-dependent interactions. If single-arm quasielastic scattering data are used, the values of $\epsilon$ can be derived from the shift in recoil energy of the quasielastic peak. Such estimates have been criticized (Noble 1981, Hotta *et al* 1984) as inconsistent, but are also claimed to ignore the effect of final state interaction (Frullani and Mougey 1984). The more accurate determination from single nucleon knockout reactions such as $(p, 2p)$ and $(e, e'p)$ show that the mean separation energy rapidly saturates with increasing $A$ at around 25 MeV, whereas a figure as high as 40 MeV has been used to explain the iron data. Indeed, other estimates (Birbrair *et al* 1986) show essentially no $A$-dependence, in conflict with the data.

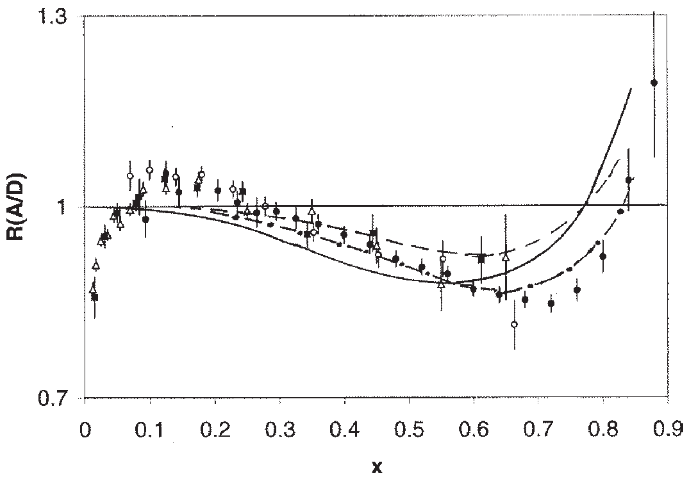


**Figure 12.** Comparison of combined data with the binding model. The data comes from Gomez *et al* 1994 (●), Ashman *et al* 1993 (■), Benvenuti *et al* 1987 (○) and Amaudruz *et al* 1995 (△). The solid line is from Akulinichev *et al* (1985a), while the (- - - -) and (— · —) lines are from Li *et al* (1988) with values of $\langle\epsilon\rangle$ of $-26$ and $-39$ MeV, respectively.

However, the direct measurements in these reactions may miss the high energy component (Ciofi degli Atti and Liuti 1989, Kulagin 1989, Shlomo and Vagradov 1989, Dieperink and Miller 1991) generated by nucleon correlations. Hence despite the introduction of the flux factor, the agreement may be at least partially recovered. It still seems surprising that such a seemingly straightforward concept as the average nucleon separation energy should generate such disagreement.

Examples of the predictions of binding models are shown in figure 12. Despite the claims often made, the agreement of the model with the data is only qualitative, and dependent on crucial parameters. It seems to be very hard to get agreement in one region of $x$ without spoiling it in another. However, it is clear that binding corrections are an ingredient in any explanation of the effect. A natural development is to include binding quanta, which will be done in the next subsection.

### *5.2. Models based on a pion enhancement*

One of the earliest models proposed to explain the EMC effect was the enhancement of the pion field in nuclei (Ericson and Thomas 1983, Llewellyn Smith 1983, Berger *et al* 1984, Titov 1984, Sapershtein and Shmatikov 1985) as a result of the attractive nucleon–nucleon interaction. For a stationary pion in the nucleus $0 < x < m_\pi/m_N$ and therefore the contribution of the pion is expected to be concentrated at low values of $x$.

The nuclear structure function is then calculated by integrating over the nucleons and pions in the nucleus.

$$F_2^A(x) = \int_z^1 f_N(z) F_2^N\left(\frac{x}{z}\right) \mathrm{d}z + \int_z^1 f_\pi(z) F_2^\pi\left(\frac{x}{z}\right) \mathrm{d}z \tag{5.7}$$

The structure functions $F_2^N$ and $F_2^\pi$ are assumed unmodified from their free-particle values, and $f_N(z)$, $f_\pi(z)$ represent the momentum distributions of the nucleons and pions in the nucleus.

There are differences of detail and method between the models. Different techniques are used, e.g. Feynman diagrams (Ericson and Thomas 1983) or light-front form dynamics (Berger *et al* 1984, Berger and Coester 1985). Bickerstaff *et al* (1986b) include a discussion on the differences between these two approaches. Based on the original EMC data, estimates were made of the excess number of pions $\langle n_\pi \rangle$ in iron required. This ranged from 6–12 (Llewellyn Smith 1983) to ∼20 (Berger *et al* 1984), compared with a nuclear physics calculation which gave 7 (Friman *et al* 1983). The discrepancy led some authors to abandon some of the simplifying assumptions of the model. The change in the data (Ashman *et al* 1988) has allowed a return to more modest values of $\langle n_\pi \rangle$ of around 7 (e.g. Głazek and Schaden (1986)). Ericson and Thomas (1983) point out that the predicted enhancement would be essentially killed if the Landau–Migdal parameter $g'_{N\Delta}$, which describes the effective repulsive interaction strength, evaluated at a three-momentum of 400 MeV c$^{-1}$, were greater than 0.8. Small changes can allow the model to predict a smaller enhancement such as the value of 0.05 per nucleon used by Miller (2001), which is in turn close to the range of 0.06–0.07 in nuclear matter suggested by Ericson and Rosa-Clot (1987) from Compton scattering on nuclei. The compatibility of the Landau–Migdal parameter as determined from different processes may prove a difficulty, since a study of Gamow–Teller excitation of the giant resonance in $^{90}$Nb (Suzuki and Sakai 1999) suggests a value as small as 0.2.

The pion model (and indeed all 'package' models in which the nucleus contains hadronic constituents other than nucleons) has often been criticized (e.g. Jaffe (1984), Jaffe *et al* (1984)) on the grounds that interference between the struck 'package' and the spectators has been neglected. This seems implausible since at low energy transfers such as encountered here there are likely to be very few if any pions in the nuclear debris or nucleons in the pion debris (e.g. Llewellyn Smith (1985)).

All the time the nucleon and pion structure functions are assumed to be the same as those for the free particles. In the formalism of Berger *et al* (1984) the particles always remain on mass-shell, but other formulations of the model have included an off-mass-shell dependence of the nucleon structure function (Dunne and Thomas 1986a), without a convincing justification. The pions themselves are also off-shell and the same questions can be raised. Furthermore, there are differences in the distributions of pion momenta in the nucleon between these different models (Bickerstaff *et al* 1986b), claimed by Berger and Coester (1985) to arise from the use of the transverse mass of the pion rather than its rest mass. However, Jung and Miller (1990) conclude that the Berger and Coester procedure is probably inaccurate.

The presence of pions in the nucleus implies also the presence of $\Delta$ resonances. Some models used $\Delta$s alone, without pions (Szwed 1983). The presence of the $\Delta$ can also produce a turndown of the EMC ratio at small $x$ (Migdal 1987). Following arguments of Farrar and Jackson (1975) the $\Delta$ is assumed to have a softer quark distribution than the nucleon and can therefore cause the depletion and slope at large $x$, but only if the iron nucleus contains 15% of $\Delta$s. Nuclear physics calculations (e.g. Friman *et al* 1983) would suggest no more than 4%. Hence models including only $\Delta$s are rather implausible. Of course, both pions and deltas can be introduced (Kubar *et al* 1984, Heller and Szwed 1985) with 'realistic' probabilities but more freedom to adjust parameters to data. Recent experimental data on $^{12}C(\gamma, \pi^+ p)$ reactions (Bystritsky *et al* 2001) and $(\pi, \pi p)$ reactions (Morris *et al* 1998, Pasyuk *et al* 2001) suggest smaller values in the region of 1–2%.

Some attempts have been made to include vector mesons as well as pions (Rozynek 1993, Burkardt and Miller 1998, Marco *et al* 1996) and the correspondence with data is usually improved. It has also been pointed out (Miller 2001) that scattering from bosons in the nucleus would enhance the longitudinal cross-section.

The general problems of the pion model are that it is difficult to make $R_{\mathrm{EMC}}$ large enough at $x = 0.2$ without spoiling the agreement at large $x$. Figure 13 shows two models taken from Bickerstaff and Thomas (1989) and deFlorian *et al* (1994). The latter claims its better

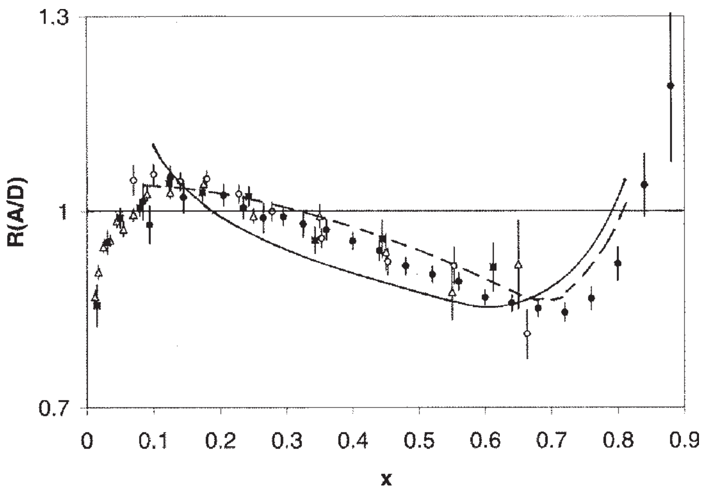


**Figure 13.** Comparison with the pion excess model. The data are as in figure 12. The solid line is from Bickerstaff and Thomas (1989) and the dashed curve from deFlorian *et al* (1994).

agreement with data is achieved by taking into account fully the corrections in deuterium. It is conventional for the experiments to express the ratio to deuterium, and models should take this into account. There is no natural explanation in this model for the shadowing that is observed at very small $x$. The pion model naturally predicts an increase in the sea in nuclei. Therefore, precise measurements of any sea enhancement as a function of $x$ have been illuminating. Further questions will emerge in the following sections.

### *5.3. Multiquark clusters*

A nucleus is dense and the nucleons in it are tightly packed together. It has been conjectured that under these circumstances the confining 'bag' may enlarge to include more than three quarks. Colour-singlet states of 6, 9, 12 etc quarks could form with a probability reflecting the fraction of the time that the nucleons are very close together and their wavefunctions overlap. The evidence that such multiquark clusters exist is at most indirect, but this can be a useful pictorial model for a nucleus and was used as an example in an early study of the EMC effect (Jaffe 1983).

The model (Carlson and Havens 1983, Daté 1983, Chemtob and Peschanski 1984, Clark *et al* 1985, Dias de Deus *et al* 1984a, b, Garsevanishvili and Menteshashvili 1984) is another example of convolution. The nucleus is assumed to consist of nucleons and six-quark clusters (and can be extended to larger clusters).

$$F_2^A(x) = \int_z^A f_N(z) F_2^N\left(\frac{x}{z}\right) \mathrm{d}z + \int_z^A f_6(z) F_2^6\left(\frac{x}{z}\right) \mathrm{d}z \tag{5.8}$$

$f_N(z)$ and $f_6(z)$ are the momentum distribution of nucleons and six-quark clusters, and $F_2^6(x)$ is the six-quark cluster structure function. The normalization

$$\int f_N(z)\,\mathrm{d}z = 1 - p, \qquad \int f_6(z)\,\mathrm{d}z = p \tag{5.9}$$

gives the probability $p$ for six-quark clusters in the nucleus.

Thus the momentum carried by the six-quark clusters is lost by the nucleons. For this mechanism to produce an EMC effect $F_2^6(x)$ should differ from $F_2^N(x)$. At large $x$ one may be guided by dimensional counting arguments (Blankenbecler and Brodsky 1974), which give $F_2(x) \sim (1-x)^{2n-1}$ where $n$ is the number of 'spectator' quarks. This means that for a $6q$ cluster one would expect

$$F_2^6 \sim \left(1 - \frac{x}{2}\right)^9 \tag{5.10}$$

since a $6q$ cluster has five spectators and the range of $x$ for such a cluster can run from zero to 2 when $F_2$ is expressed as the structure function per nucleon. This formula is only expected to be valid at very large $x$, but it shows two features needed to confront the experimental data. It has a softer $x$ distribution (as might be expected since the $6q$ bag should be larger than a nucleon and a larger spatial extent implies softer momenta) and a hard tail which can explain the rapid rise in $R_{\mathrm{EMC}}$ at very large $x$.

The most developed model appears to be that of Lassila and Sukhatme (1988) which can reproduce the turnover of the EMC ratio at small $x$. It uses updated and improved parametrizations of cluster structure functions, and a new model for the $A$-dependence (figure 14). It is claimed that agreement with data would be improved by the addition of $9q$ clusters. Despite these good features the model does not have much predictive power. No one has ever seen a $6q$ cluster and its structure function and momentum distribution have to be guessed. Clark *et al* (1985) pointed out that any two-component model could give a reasonable

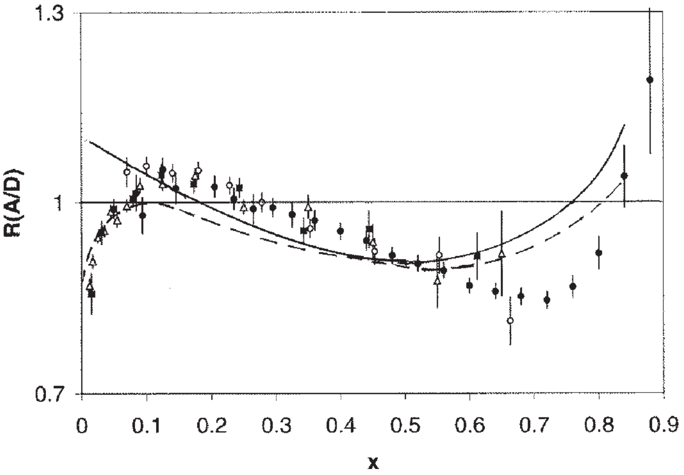


**Figure 14.** Comparison of combined data (as in figure 12) with the quark cluster model. The solid line is from Carlson and Havens (1983) and the dashed line from Lassila and Sukhatme (1988).

representation of the data available at that time. Like in the pion model, the second component consisting of $6q$ clusters would be bosonic, and therefore give rise to an enhanced longitudinal to transverse cross-section ratio, whereas no effect has so far been seen.

Other authors give special place to the $\alpha$ particle as the 'second component' (Faissner and Kim 1983, Faissner *et al* 1984, 1985, Kondratyuk and Shmatikov 1984, 1985). Such models predict a particularly strong EMC effect in nuclei such as $^{12}$C which can be more completely factorized into $\alpha$ clusters. No strong evidence of such behaviour is apparent in the data.

Evidence for multiquark clusters has long been sought. 'Cumulative production' of particles beyond the kinematic limit for stationary nucleons (Baldin *et al* 1974, Baldin 1985) gave some indication, as did the high-$Q^2$ behaviour of the deuteron form factor ($Q^{-10}$, as expected for a six-quark state) observed by Arnold *et al* (1975). Multiquark admixtures were also used by Pirner and Vary (1981) to explain inelastic data from $^3$He, for which a six-quark bag probability of 16% was needed, and Burov *et al* (1984) proposed 8% from a study of the $^3$He form factor. Of course, a six-quark admixture in the deuteron itself is an old idea (e.g. Matveev and Sorba (1977)). Estimates for the six-quark probability range from 4% to 7% (Burov *et al* 1982, Kisslinger 1982, Dorkin *et al* 1984, Bhaduri and Nogami 1985, Sato *et al* 1986, Yen *et al* 1990), a value given support by high energy deuteron fragmentation on nuclei (Ableev *et al* 1983) to 1–2% in other models (Kalashnikova *et al* 1986, Yamauchi and Wakamatsu 1986). With such variation in the prediction for the deuteron, it is clear that for higher-$A$ nuclei the predictions may be even more variable. For iron, the estimates vary from as high as 30% (Carlson and Havens 1983, Lassila and Sukhatme 1988) to 20% (Garsevanishvili *et al* 1989) and 18% (Vary 1984) with some authors also including nine-quark clusters. The variation between these models shows the sensitivity to the many parameters of the model. It should be pointed out that any significant EMC effect in the deuteron, such as six-quark clusters, would affect the extraction of the neutron structure function $F_2^n$ from deuterium data. There is no sign of a large effect in a comparison of muon and neutrino scattering (Bodek and Simon (1985), and see also Mulders and Thomas (1984)), although the experimental errors are large.

Some other approaches to the EMC effect are similar in concept and execution to the multiquark cluster model. For example, a specific three-gluon force (Barshay 1985) is rather similar to a nine-quark cluster. The existence of a distinct quark–diquark structure to the nucleon, with the diquark modified by the nuclear medium, has also been proposed (Fredriksson 1984). The valon model (e.g. Zhu *et al* (1985), Zhu and Shen (1989)) pictures nucleons as three 'valons' or valence quarks dressed with sea and gluons. These valons are assumed to be influenced by the nuclear medium only in their momentum distribution. It should also be pointed out that the 'flucton model' is essentially the same in its consequences as the multiquark cluster models (e.g. Zotov *et al* (1984)).

The multiquark cluster model makes clear predictions for the behaviour of $F_2^A$ at $x_N > 1$, a region forbidden for free nucleons. There is now some data (Day *et al* 1993) which is difficult to explain by conventional high momentum tails, but it cannot be regarded as conclusive evidence for multiquark clusters. Predictions have also been made for the effect on the gluon distributions in nuclei (Sukhatme *et al* 1992).

### 5.4. Dynamical rescaling

The ideas for dynamical rescaling arose from the observation (Close *et al* 1983) that the iron structure function of the original EMC data resembled the deuterium structure function at a higher value of $Q^2$. This is equivalent to stating that $R_{\mathrm{EMC}}$ follows the pattern of scaling violation of the structure functions. $F_2$ per nucleon on a nucleus $A$ is

$$F_2^A(x, Q^2) = F_2^N(x, \xi_A(Q^2)Q^2) \tag{5.11}$$

where $\xi_A$ is the 'rescaling factor' in $Q^2$. This itself is unremarkable, except that $\xi_A$ takes a value of around 2 for iron and is, within errors, independent of $x$.

This behaviour was interpreted as a change in the quark confinement scale of a nucleon in a nucleus, a suggestion made earlier in another context (Jaffe 1983), and later by others (Cleymans and Thews 1985). The scaling is 'dynamic' in the sense that when $Q^2$ changes in QCD the quark, antiquark and gluon distributions evolve. Momentum transfers $Q^2$ are expressed in terms of a scale $\mu^2$ which is the renormalization point, and no physical quantities can depend on $\mu^2$. Close *et al* argued that $\mu^2$ could be interpreted as a scale in which the nucleon consisted of valence quarks only, a starting point for QCD evolution, and that in a nucleus, this scale $\mu_A^2$ would be smaller. The presence of neighbouring nucleons had generated more evolution at the same value of $Q^2$. $\mu_A^2 = \mu_N^2/\xi_A(\mu_N^2)$, and the $Q^2$ evolution can be used to demonstrate that

$$\xi_A(Q^2) = \left[\frac{\mu_N^2}{\mu_A^2}\right]^{\alpha_s(\mu_N^2)/\alpha_s(Q^2)} \tag{5.12}$$

Although $\xi_A$ depends upon $Q^2$, so do the structure functions themselves, and quite a weak $Q^2$ dependence is expected in $R_{\mathrm{EMC}}$ (e.g. Bickerstaff and Miller (1986a, b)).

In order to make predictions for the $A$-dependence of the effect, some model was needed for the change of confinement scale. It was assumed that a confinement size $\lambda$, given by

$$\frac{\lambda_A^2}{\lambda_N^2} = \frac{\mu_N^2}{\mu_A^2} \tag{5.13}$$

could be related to the nuclear density and the probability for nucleons to overlap. The value of $\xi = 2$ at $Q^2 \sim 50\,\mathrm{GeV\,c^{-2}}$ implies an increase in confinement size in iron of about 15%. The predictions of this model (Jaffe *et al* 1984, Close *et al* 1985b) for the $A$-dependence are in good agreement with the SLAC data (Arnold *et al* 1984). The same model has been extended to give predictions for a relationship between nucleon and pion structure functions (Close *et al* 1984, Bickerstaff *et al* 1985).

The model is applicable only in the intermediate $x$-range $0.2 \leqslant x \leqslant 0.9$ since at large and small $x$ there are substantial next-to-leading order QCD corrections. It makes no attempt to

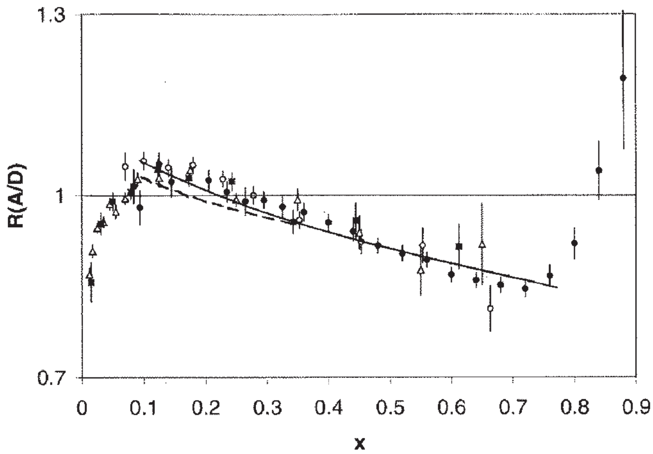


**Figure 15.** Comparison with the dynamical rescaling model. The data are as in figure 12. The solid and dashed curves are for different ranges of $Q^2$ corresponding to the SLAC and EMC data, respectively (Close *et al* 1985a).

describe the data for $x \gtrsim 0.65$, since Fermi motion is not included. The model gives results in reasonable accord with the data as a function of $x$, but it cannot reproduce precisely the value of $x$ where $R_{\mathrm{EMC}} = 1 (\sim 0.25)$ since it is forced to follow the pattern of scaling violations, which vanish at $x \sim 0.15$ (figure 15). Parton recombination (section 5.5) may help to explain this. Bickerstaff and Miller (1986a) point out that the similar results from conventional models and dynamical rescaling imply that the latter mimics binding effects. Close *et al* (1986, 1988) have taken this a stage further and attempted to relate QCD scales to the parameters associated with nuclear binding and thus ‘derive’ binding from QCD. While the two are undoubtedly related, this seems very ambitious in the light of the very different predictions of different forms of the binding model.

At about the same time as dynamical rescaling was proposed, another related model was presented (Chanfray *et al* 1984, Nachtmann and Pirner 1984, Pirner 1984) in which the deconfinement of quarks grew with $Q^2$. At low $Q^2$ quarks are confined within nucleons. At higher $Q^2$ their range extends until at very high $Q^2$ the nucleus becomes a ‘colour conductor’: the confinement size is the size of the nucleus and quarks and gluons are ‘free’. The scaling parameter here is the ratio of the squares of the nuclear radii $R_A^2/R_N^2$, and the structure function $F_2(x, Q^2, A)$ becomes a universal function $F_2(x, R_A^2 Q^2)$. This hypothesis seems not to agree with data: although it is difficult to refute it with heavy nuclei, $^4$He presents it with problems. $^4$He has a smaller radius than nearby nuclei, and is denser. It has already been pointed out that it gives an anomalously large EMC effect, whereas in this model the smaller radius would give rise to a smaller than typical EMC effect. In this and related models (e.g. Gupta (1985), Gupta and Sarma (1985), Gupta *et al* (1985)) one has the unattractive feature that the QCD scale parameter $\Lambda$ becomes $A$-dependent.

The radical proposal that quarks are deconfined in a nucleus was made many years ago (Krzywicki 1976) in an attempt to explain the production of high $p_{\mathrm{T}}$ hadrons from nuclei. The same ideas have been used in thermodynamic models (Angelini and Pazzi 1985) and quark tunnelling (Goldman and Stephenson 1984). While these effects are unlikely to describe real nuclei, it should be remembered that a phase transition between confined and deconfined quarks and gluons is expected in QCD at higher densities giving rise to a ‘quark–gluon plasma’ (e.g. Baym (1979)).

The change in confinement scale has been interpreted by some authors as a 'swelling' of nucleons within a nucleus, used in phenomenological models (Hendry *et al* 1984, 1986), colour dielectric models (Mathieu and Watson 1984) and soliton models of the nucleus (Jändel and Peters 1984, Celenza *et al* 1985a). However such a swelling is not necessarily automatic. The quark may have a greater penetration range in nuclear matter, for example by quark exchange between nucleons, which can modify the quark momentum distribution (Bräuer *et al* 1985, Hoodbhoy and Jaffe 1987).

### *5.5. Shadowing*

Shadowing of real and virtual photons is a long-established effect (see, e.g. Bauer *et al* (1978)). It was mostly described in the rest frame of the nucleus. The photon coupled to hadronic states with the same quantum numbers which then interacted hadronically with the nucleus. Interference between single and multiple interactions caused the reduction in the cross-section known as shadowing. Initially the hadronic state was just the low-lying vector mesons $\rho$, $\omega$ and $\phi$, but this was later generalized to towers of vector mesons, and off-diagonal interactions in which a vector meson scattered inelastically to reappear as a different vector meson. The result of the generalization was that the $Q^2$-dependence of $1/Q^2$ was softened considerably and an approximate independence of $Q^2$ was achieved, in agreement with data. Indeed, these old models were restated after the EMC results were released (Shaw (1989), Bilchak *et al* (1988), which contain the relevant references). A possibly equivalent description is in terms of the photon coupling to $q\bar{q}$ pairs and the interaction of the pairs with the target being large for pairs of high relative transverse momentum and low otherwise (Frankfurt and Strikman 1988, Piller *et al* 1995).

In an extraordinarily perceptive paper, Nikolaev and Zacharov (1975) noticed that in a parton model, the coherence length of the virtual photon became large at low $x$ and that individual nucleons could not be resolved. Their conclusion was that low-$x$ partons would fuse, giving rise to shadowing at low $x < 0.1$ and antishadowing at slightly larger $x$. The shadowing behaviour exhibits scaling (independence of $Q^2$) in this parton model, and also in a QCD analysis (Nikolaev and Zacharov 1991), whereas in most other models shadowing is a higher twist effect and falls off as $1/Q^2$. There is clearly a conflict of opinion here: Kharzeev and Satz (1994) argue that shadowing and antishadowing are quantum mechanical interference effects and cannot be interpreted in terms of modified parton distributions, a position also taken by Brodsky *et al* (2002), who dispute the identity of measured structure functions and parton probability distributions. This has implications for the identity of parton distributions in deep inelastic scattering with those derived from other hard processes.

In the parton recombination model of Qiu (Mueller and Qiu 1986, Qiu 1987, Berger and Qiu 1988, Close *et al* 1989), the struck parton's momentum is modified by prior fusion interactions in the nuclear medium. Although the fusion appears to be a higher twist process, the $1/Q^2$ trend is compensated by the fast rise in the gluon distribution at low $x$, and the overall $Q^2$ dependence is expected to be very weak, in accord with data. This can also help to resolve the discrepancy between data and model in dynamical rescaling where the vanishing of the EMC effect occurs at higher $x$ than in the model (Close and Roberts 1988). However, the $A$-dependence of the details of the EMC effect as predicted by Close and Roberts do not seem to be confirmed by the most recent data.

There are therefore two different views of shadowing: one applicable in the target rest frame and dependent on interference between single and double scattering; the other applicable in the infinite-momentum frame and predicting a scaling behaviour of shadowing. It is not clear whether these two pictures are in some way equivalent and it is certailnly not easy to reconcile them.

This has been a very cursory description of models of shadowing, and many more details can be found in other reviews (e.g. Arneodo (1994), Piller and Weise (2000)).

## 6. Other processes

The consequence of the EMC effect is that the quark distributions in a nucleon are modified when the nucleon is embedded in a nucleus. One should therefore expect to see evidence for the effect in other processes which can be described by the quark–parton model. This of course assumes QCD factorization, in which the parton distributions are process-independent. This appears to be a good assumption. Some of these other processes will now be considered.

### *6.1. The Drell–Yan process*

In hadron–hadron scattering a quark from one hadron can annihilate with an antiquark from the other, producing a timelike virtual photon which couples to a pair of charged leptons (Drell and Yan 1970). This is clearly a process which is dependent on the quark distributions (structure functions) of both the projectile and target and can shed light on the EMC effect since it has been normal to use heavy targets to achieve a sufficient event rate. Many experiments have been performed with various beams and targets and the reader is referred to a recent review (McGaughey *et al* 1999) for details.

The differential cross-section for Drell–Yan pair production may be written as

$$\frac{d^2\sigma}{dx_1\,dx_2} = K\frac{4\pi\alpha^2}{9s}\sum_i e_i^2\{q_{i\mathrm{P}}(x_1)\bar{q}_{i\mathrm{T}}(x_2) + \bar{q}_{i\mathrm{P}}(x_1)q_{i\mathrm{T}}(x_2)\} \tag{6.1}$$

where the suffices P, T refer to the projectile and target particle, $\sqrt{s}$ is the centre of mass energy of the projectile–target nucleon system and $x_1$, $x_2$ are the momentum fractions carried by the quarks (or antiquarks) in the projectile and target, respectively. This form, which is a pure parton model calculation, is retained in QCD if factorization holds. The factor $K$, which experimentally is around 2 with at most a weak kinematic dependence, represents the departure from the simple parton model and can be calculated in higher order QCD with the summation in all orders of the effects of soft gluons. The cross-section may also be expressed as a function of the mass and the Feynman variable $x_\mathrm{F} = 2p_\parallel/\sqrt{s}$ or the rapidity $y$ of the muon pair by the relations (where $p_\parallel$ is the momentum of the muon pair in the c.m. frame parallel to the beam)

$$x_\mathrm{F} = x_1 - x_2, \qquad M^2\sqrt{s} = x_1x_2 = \tau \qquad x_1 = \sqrt{\tau}\,e^y, \qquad x_2 = \sqrt{\tau}e^{-y} \tag{6.2}$$

The range of $x_1$ and $x_2$ which can be covered is restricted. Limitations of acceptance usually demand $x_\mathrm{F} \gtrsim 0$. The usable $\tau$ range is limited at the low end by the low value of $M^2$ (below which the parton model will not be valid) and at the high end by the poor statistics. A typical experiment can cover $0.2 < x_1 < 1.0$ and $0.1 < x_2 < 0.6$, with most of the data concentrated at low $x_1$ and $x_2$.

The Drell–Yan process thus probes the quark and antiquark content of both the beam and the target hadron. For data taken with pion beams, over most of the range of $x_\mathrm{F}$, the second term in the equation is dominant because of the valence antiquarks in the pion. The Drell–Yan ratio should follow $R_\mathrm{EMC}$ (Chmaj and Heller 1984, 1985, Dias de Deus *et al* 1984a, Berger 1986, Close *et al* 1985b). Early experiments were not sufficiently precise or not designed to compare different targets but the first to do so (Bordalo *et al* 1987) showed the expected effect. Probing low $x_2$ would be very interesting as independent confirmation of $R_\mathrm{EMC}$ in this region, but it is difficult to ensure a high enough value of $M$ to guarantee the validity of the Drell–Yan model.

For proton beams, $\bar{q}(x_1)$ is very small for $x_1 \gtrsim 0.2$ and thus the first term in equation will dominate for $x_F > 0$. Thus the ratio of the Drell–Yan cross-sections on different nuclear targets will tend to reflect the ratio of the antiquark distributions in the different nuclei. This is a powerful method of measuring any sea enhancement in nuclei, as has been pointed out by many authors (Bickerstaff *et al* 1984, Gabellini *et al* 1985, Close *et al* 1985a) and can help to distinguish between models of the EMC effect which each represent the structure function ratios correctly. As an example (Berger 1986) some pion models predict a broadening of the nuclear sea because of the presence of valence antiquarks in the pion, whereas in the dynamical rescaling model the sea would get narrower, following the QCD evolution. Comparisons have also been made (Bickerstaff *et al* 1984) with six-quark cluster models. For negative values of $x_F$ (very difficult experimentally) $x_2$ will be large and the second term in equation dominates. The Drell–Yan ratio should then follow the structure function ratio of the different nuclei.

Measurements of the proton–nucleus Drell–Yan process (Alde *et al* 1990) show the remarkable behaviour of figure 16. The ratio fails to rise at small $x$ in contradiction to most of the models. It should be pointed out that the rise above unity in the ratios of structure functions must be an effect of the valence quarks and not the sea quarks since no enhancement is seen in the Drell–Yan ratio.

The behaviour of the ratio has been claimed to present a particular difficulty for pion and dynamical rescaling models of the EMC effect, although the dynamical rescaling model may not be relevant in this range of $x$. One formulation of the quark cluster model claims success (Lassila *et al* 1991), and some more recent pion models (e.g. Dieperink and Korpa (1997), de Florian *et al* (1994)) do not predict an enhancement at low $x$, nor do they predict the turn-down at very small $x$ which may be associated with shadowing in deep inelastic scattering. One important feature is that these (Alde *et al* 1990) and subsequent data (Vasiliev *et al* 1999) are described well by a fit to the existing shadowing observed in deep inelastic scattering. Hence models which fit the low $x$ region in deep inelastic scattering should also fit low $x_t$ data in Drell–Yan production. This raises important questions about the origins of shadowing, since the quantum mechanical interference effects supposedly responsible for shadowing in deep inelastic scattering may have no role in Drell–Yan. This is a complex issue still being discussed (e.g. Peigné (2002)).

Many other features of the Drell–Yan process, such as the $p_T$ of the lepton pair and its dependence on $A$, the possibility of energy loss of initial state partons (Johnson *et al* 2002),

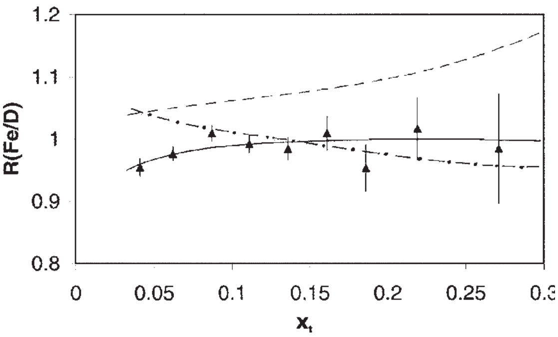


**Figure 16.** Drell–Yan cross-section ratios of Fe to deuterium from Alde *et al* (1990) for a target of Fe. The solid curve is from a quark cluster model (Lassila *et al* 1991), the dashed curve from the pion model of Hwang *et al* (1988) and the dot-dash curve from the dynamical rescaling model (Close *et al* 1985b).

and multiple parton–nucleon scattering are of great interest, but they are not discussed here because of lack of space (see McGaughey *et al* (1999)).

The Drell–Yan process has been used extensively as a test of QCD via the $K$-factor and the muon pair transverse momentum, and as a means of measuring the pion structure function. It is clear that any underlying nuclear effects must be understood before definitive conclusions on QCD tests or on the pion structure function can be drawn.

### 6.2. High $p_T$ hadron production by hadrons

The production of hadrons at high $p_T$ can be described by the scattering of partons which are constituents of both beam and target particles and which fragment into hadrons after the hard scattering. At high values of $x_T (= 2p_T/\sqrt{s})$, which implies large values of Bjorken $x$ of the incident partons, the EMC effect would predict a reduction of the cross-section on heavy targets (Close *et al* 1985b).

However, it is well known experimentally that in fact such production on heavy nuclei is enhanced (Cronin *et al* (1975), Antreasyan *et al* (1979), Hsiung *et al* (1985) and references therein): it can be parametrized as $A^\alpha$ with $\alpha > 1$, typically $\alpha \gtrsim 1.1$ for $p_T > 3\,\mathrm{GeV\,c^{-1}}$. The enhancement is even greater for jet production (Bromberg *et al* 1979), and has also been seen in $\alpha$–$\alpha$ collisions at much higher energies at the CERN ISR (Angelis *et al* 1982, Åkesson *et al* 1982).

These effects are usually ‘explained’ by a constituent multiple scattering model (Krzywicki *et al* 1979, Lev and Petersson 1983): rare high $p_T$ final states are enhanced by multiple scattering in the nucleus from partons produced at lower $p_T$. Further results from FNAL (Stewart *et al* 1990, Corcoran *et al* 1991) support the multiple scattering picture, and one must conclude that high $p_T$ hadron production and jet production by hadron beams on nuclei can tell us little about the EMC effect.

At very high $x$, an enhancement could result from the rise in $R_{\mathrm{EMC}}$ at high $x$ from Fermi motion or from the presence of multiquark clusters in nuclei. Gupta and Godbole (1986a, b), and Godbbole and Gupta (1989) have investigated various models which fit the EMC data and claim some can indeed reproduce a rising trend for $\alpha$ for jet cross-sections. None of these give agreement with the data: a pure six-quark bag model shows very little effect, whereas a ‘Fermi gas model’ of deconfined quarks gives $\alpha$ rising with $p_T$, but its magnitude is well below the data.

Finally, it is interesting that the first prophetic predictions of an enhancement of structure functions at small $x$ in nuclei (Krzywicki 1976) came from an attempt to understand high $p_T$ hadron production using a model of quark deconfinement.

### 6.3. $J/\psi$ production

The processes described so far have been related to the quark and antiquark distributions of nuclei. Since quarks and gluons are so intimately coupled, modifications to the gluon distribution must also be expected. Only indirect information on the gluon distribution can be obtained from deep inelastic scattering, but a more direct, albeit model-dependent, determination can be made from the muoproduction of charmed quark pairs.

Because of the large mass of the charmed quark, QCD can be used to calculate the production of $c\bar{c}$ pairs. The photon–gluon fusion model was used to relate the $J/\psi$ production to the gluon density (e.g. Aubert *et al* (1983c)), but the model ignores the colour-neutralizing soft gluon which must be exchanged for the $J/\psi$ to be a colour singlet. The general opinion is now that inelastic $J/\psi$ muoproduction, where the colour neutralizing gluon is hard, gives a more reliable measure of the gluon distribution (Berger and Jones 1981), and this model has been used extensively (e.g. Ashman *et al* (1992), Allasia *et al* (1991), Martin *et al* (1987), with more recent QCD corrections by Krämer (1996)). Despite this, diffractive $J/\psi$ production has also been advocated as a measure of the gluon distribution (Ryskin *et al* 1997, Kharzeev *et al* 1999), but coherent effects on nuclear targets must be corrected for to obtain a gluon EMC effect.

The only data comparing different nuclear targets in inelastic $J/\psi$ muoproduction is from NMC (Amaudruz *et al* 1992c), in which production on tin was greater than on carbon by a factor $1.13 \pm 0.08$ in the $x$ range between 0.05 and 0.15. They also found a suppression of quasielastic production on tin, as had been seen earlier in photoproduction (Sokoloff *et al* 1986). The observed gluon modification is consistent with that derived by Gousset and Pirner (1996) from a study of the high statistics $F_2^{\mathrm{Sn}}/F_2^{\mathrm{C}}$ measured by NMC.

An increase in the gluon distribution in nuclei at small $x$ is predicted in the dynamical rescaling model (Dias de Deus *et al* l984b, Close *et al* l985b), following the evolution of the gluon distribution. Pion models presumably would also give an enhancement from the gluon distribution of the pion at small $x$.

The hadroproduction of $J/\psi$ can also in principle shed light on the gluon distribution in nuclei. Examples are the Fermilab experiments E789 and E866 (Leitch *et al* (1995, 2000), where references to other experiments can be found), and the CERN heavy ion experiment NA38 (Baglin *et al* 1991). These experiments usually express the $A$-dependence of the cross-sections as $A^\alpha$ and $\alpha$ is typically significantly less than unity. However, other factors can produce an $A$-dependence, including energy loss and scattering of the incident projectile before the interaction, subsequent scattering of the $J/\psi$ after the interaction and dissociation of the $J/\psi$ by co-moving spectator partons. Finally, the $J/\psi$ is expected to be suppressed by the formation of a quark–gluon plasma in heavy ion collisions (Matsui and Satz 1986), later observed in Pb–Pb collisions (Abreu *et al* 2000). For all these reasons, the hadronic production of $J/\psi$ cannot be expected to yield direct information on the EMC effect for gluons.

### *6.4. Direct photon production*

The direct production of prompt photons can arise from $q\bar{q}$ annihilation to $g\gamma$ or from quark bremsstrahlung, $qg \rightarrow q\gamma$ (Ballocchi and Zieliński 1986). The cross-sections are therefore sensitive to both the quark and gluon distributions in the target. In particular, proton beams (with no valence antiquarks) are particularly sensitive to the gluonic content (Gupta and Sridhar 1987, Sridhar 1992). The predicted $A$-dependence of the gluon distribution is significantly different in different models.

The initial parton (but not the produced photon) can suffer multiple scattering in the nuclear medium, and so modify the $p_{\mathrm{T}}$ distribution, as is proposed in high $p_{\mathrm{T}}$ production of hadrons (Guo and Qiu 1996). While this analysis is very interesting, cast in the style of $A^\alpha$ dependence, it does not focus on the gluon content of nuclei.

Data is particularly sparse. The E706 experiment at Fermilab (Alverson *et al* 1993) is restricted to Be targets and is more concerned about $p_{\mathrm{T}}$ effects. Although data has also been taken on copper, no comparisons of the gluon distributions appear to have been made. More recent papers stress the discrepancies with QCD which can only be reconciled by the introduction of a large $k_{\mathrm{T}}$ effect from the soft gluon radiation from incident partons (Apanasevich *et al* 1999, 2001). It has become clear that it will be some time before direct photon production can shed light on the gluon EMC effect. Direct photon production is important in looking for signs of the quark–gluon plasma in heavy ion collisions, but other corrections can have as big an effect as gluon shadowing, and it is unlikely that nuclear gluon distributions can be determined unambiguously in this way (Jalilian-Marian *et al* 2002).

## 7. The EMC effect and nuclear physics

The conventional description of the nucleus in nuclear physics is in terms of nucleons which are bound together by a potential. The degrees of freedom are those of the constituent nucleons, with additional effects from the mesons which cause the binding. On the other hand, deep inelastic scattering usually refers to quarks as the constituents, and the EMC effect demonstrates that the nucleon's properties in the nucleus must be modified.

In this section I shall give a brief account of some areas of nuclear physics which are relevant *a posteriori* to the EMC effect. This is not a full-scale review of the subject, but highlights some areas which may be of some relevance. There are many results in nuclear physics which demand further degrees of freedom of the nucleus than just single nucleons.

### *7.1. Quasielastic electron scattering and y-scaling*

*7.1.1. Inclusive quasielastic scattering.* In electron scattering from nuclei the quasielastic peak, scattering from the nucleons in the nucleus, shows up clearly. The electron spectrum at fixed scattering angle shows a peak which is broadened by the Fermi motion of the nucleons and the electron momentum is shifted compared with that on hydrogen, because of the binding of the nucleons. Data of this sort are a prime source of information on Fermi momenta and nucleon separation energies (e.g. Whitney *et al* (l974)). However, the correspondence between the shift of the peak and the average nucleon separation energy is not universally accepted (Rosenfelder 1980, Noble 1981, Hotta *et al* 1984).

If the nucleon's properties were modified in a nucleus (Mulders 1990), in particular its size, then one would expect to be able to measure a modification of the nucleon form factor from its free nucleon value. In single arm inclusive quasielastic experiments the broadening of the peak causes an overlap between the peak, the 'dip region' and the opening up of inelastic channels (figure 17), and since the $A$-dependence of the latter two is not known *a priori*, the quasielastic cross-section has to be extracted using a model. Early experiments (Moniz *et al* 1971, Whitney *et al* 1974) gave good and consistent agreement with the Fermi gas model (Moniz 1969).

The Rosenbluth method can be used to separate the transverse and longitudinal responses in quasielastic scattering, by varying the beam energy and scattering angle while keeping $Q^2$ fixed. The transverse and longitudinal response functions $R_L$ and $R_T$ are given by

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E'\,\mathrm{d}\Omega} = \sigma_M\left(\frac{Q^4}{|\boldsymbol{q}|^4}R_L + \left(\tan^2\left(\frac{\theta}{2}\right) + \frac{Q^2}{2|\boldsymbol{q}|^2}\right)R_T\right) \tag{7.1}$$

where $\sigma_M$ is the Mott cross-section and $q$ is the three-momentum transfer. $R_L$ and $R_T$ depend on $q$ and $\omega$, the energy transfer $E - E'$ (Boffi *et al* 1996). $R_L$ and $R_T$ represent the charge and current densities, respectively (analogous to electric and magnetic form factors). The single-particle aspects of the scattering may be deduced from the behaviour of $R_L$ while $R_T$ also includes the effects of meson exchange currents, $\Delta$ excitations and two-particle two-hole excitations. Hence $R_L$ is the response function most closely relevant to any modification of the properties of the nucleon. A further property of $R_L$ is that its integral is the subject of a fundamental sum rule, the Coulomb sum rule or CSR (deForest and Walecka 1966), which is

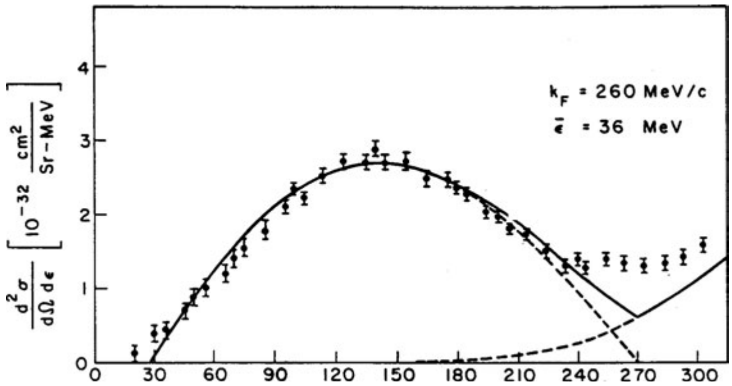


**Figure 17.** Quasielastic scattering spectra from Ni as a function of the electron energy loss $\nu$: the free proton would give a peak at 105 MeV (from Moniz *et al* (1971)).

written as:

$$S_L(q) = \frac{1}{Z}\int_0^\infty \frac{R_L(q,\omega)}{\tilde{G}_E^2}\,d\omega \tag{7.2}$$

$\tilde{G_E}$ is the electric form factor averaged over the nucleons. The integral should tend to unity at large $q$ when the nucleon–nucleon correlations imposed by Pauli blocking are absent. Note that the lower limit of integration excludes the nuclear elastic peak.

Measurements of separated quasielastic cross-sections on $^{56}Fe$ were made over 20 years ago (Altemus *et al* 1980); the behaviour of $R_T$ was in broad agreement with a relativistic Fermi gas calculation, whereas $R_L$ showed a marked reduction (about a factor of 2) compared with the same model. This effect is usually described as the 'quenching' of the longitudinal response $R_L$ and implies a violation of the Coulomb sum rule. This result was interpreted (Noble 1981) as an increase of the charge radius of the nucleon in nuclear matter of around 30% accompanied by a change in the effective nucleon mass from $M$ to $M^*$ such that

$$\frac{r}{r_{\text{free}}} = \frac{M}{M^*} \tag{7.3}$$

Such scaling arises naturally in bag models. Noble also claimed that the free nucleon anomalous magnetic moments were also modified in the nucleus (see also Mulders (1985)). Any such model is likely to underestimate $R_T$, and Noble accommodated this by a large contribution from meson-exchange currents, a procedure which had its critics (Zimmerman 1982).

Further data on other targets followed, with many (but not all) showing quenching of $R_L$. The Coulomb sum rule is valid only for uncorrelated non-relativistic nucleons, and corrections are required. Furthermore, the integral cannot be measured fully at finite energies and an extrapolation needs to be made beyond the maximum value of $\omega$ measured. The possibility of missing strength in this unobserved region of $\omega$ has been disputed on theoretical grounds (Noble 1983) and an experiment with a much larger span in $\omega$ (Baran *et al* 1988) sees insufficient strength to satisfy the sum rule.

Not all experiments made similar corrections and extrapolations, and care must be taken in interpreting the conclusions. The general consensus is that there is no quenching observed on the nuclei $^2H$, $^3H$ and $^3He$ (Marchand *et al* 1985, Dow *et al* 1988, Dytman *et al* 1988, Meziani *et al* 1992) although the error bars are often large. Agreement between data and models is usually worse for low values of three-momentum transfer, where corrections for nucleon–nucleon correlations are needed. For $^4He$ the situation is less clear, and rather dependent on corrections and extrapolations. Some results (von Reden *et al* 1990, Meziani *et al* 1992) favour no quenching, while another (Zghiche *et al* 1994) reports a 14% quenching of $R_L$, although the discrepancy is smaller at the highest value of $|\boldsymbol{q}|$.

For heavier nuclei the data show conflicting results. For $^{12}$C (Barreau *et al* 1983) no quenching is observed. For Ca the experiments disagree: Deady *et al* (1983) observe 90% of the Coulomb sum at a three-momentum transfer of 410 MeV c$^{-1}$, whereas other measurements (Meziani *et al* 1984, Deady *et al* 1986) exhibit quenching as large as 30%. The most recent data (Yates *et al* 1993, Williamson *et al* 1997) show no quenching within the experimental errors. For $^{56}$Fe, Meziani *et al* (1984) report a quenching of 20% at three-momentum transfers greater than twice the Fermi momentum, while Chen *et al* (1991) report a Coulomb sum below model predictions, with no dependence on $|\boldsymbol{q}|$. Finally, there is a clear discrepancy between data on $^{238}$U (Blatchley *et al* 1986) and $^{206}$Pb (Zghiche *et al* 1994). The former shows quenching at low $|\boldsymbol{q}|$ which tends to zero by 500 MeV c$^{-1}$; the latter has a 50% quenching which appears to grow with $|\boldsymbol{q}|$. Suggestions have been made of significant systematic errors associated with the Rosenbluth separation of $R_L$ and $R_T$, particularly in the behaviour of spectrometers at low electron momenta, where scattering from magnet poles and vacuum vessels can introduce background (Chen *et al* 1991). A further complication is that for heavier nuclei the assumption of an incoming and outgoing plane wave will no longer be sufficient: the nucleus accelerates and focusses the beam electrons, and corrections must be made in a consistent way to extract the response functions. A reanalysis of the data from all experiments, rather than from individual ones, has been made (Jourdan 1995, 1996), with the striking conclusion that no quenching was visible. Jourdan included high energy SLAC data taken at small angles in order to achieve a better lever arm for the Rosenbluth separation. He also used precise fits to the free proton form factor, relativistic corrections, a correction for Coulomb distortion, and an estimate of the 'tail' contribution above the maximum of $\omega$ achievable in the data. Nevertheless, this result was controversial. Different calculations of the Coulomb distortion corrections disagree (Traini 2001), but can be checked using recent data on e$^+$ and e$^-$ quasielastic scattering on $^{12}$C and $^{208}$Pb (Guèye *et al* 1999). If a different prescription from that of Jourdan is used (Morgenstern and Meziani 2001) quenching for heavy nuclei is restored at the level of 20–30%. This would correspond to a change of the proton charge radius in a nucleus of $13\pm4$% at a three-momentum transfer of about 500 MeV c$^{-1}$, still substantial, but less than the 30% inferred from the early EMC data. Further reported measurements of the CSR on $^4$He using world data (Carlson *et al* 2003) record no change of the form factor in the nucleus, the result depending on the presence of two-body exchange currents (meson exchange currents). It is clear that there are very divided opinions on this issue.

What is really needed to establish whether there is a change in the charge radius is data at much higher momentum transfer. This is difficult for heavy nuclei, since the large Fermi momentum causes an overlap between the quasielastic and inelastic regions.

*7.1.2. Semi-inclusive quasielastic scattering.* Quasielastic scattering has also been investigated through detection of the recoil proton in semi-inclusive reactions $A(e, e'p)A'$. The recoil mass can be determined and high inelasticities, where many-body effects can occur, can be avoided. Information is also obtained on the nuclear shell from which the proton was ejected. The final state interaction of the proton as it emerges from the nucleus presents a problem which is usually treated in the optical model, and corrections must also be made for neutron interactions with subsequent charge-exchange in the nucleus. For the most part, only relatively light nuclei have been measured.

The cross-section now includes four structure functions which reflect the interference between longitudinal and transverse amplitudes. If the proton is detected parallel to the momentum transfer $\boldsymbol{q}$ then only the standard longitudinal and transverse responses remain; they can be separated by the usual Rosenbluth method, and a ratio of these responses can be obtained, in which many effects of the nucleus cancel. Measurements made on $^{12}$C (van der Steenhoven *et al* 1986), $^{6}$Li (van der Steenhoven *et al* 1987), $^{40}$Ca (Reffay-Pikeroen *et al* 1988) and $^{4}$He (Ducret *et al* 1993b) show a consistent quenching of the longitudinal response, but none is seen for $^{3}$He (Ducret *et al* 1993a) when a sufficiently high $\boldsymbol{q}$ has been reached. The quenching in all cases seems not to depend on $\boldsymbol{q}$ and is interpreted as an increase in the bound proton magnetic moment rather than a change in either electric or magnetic form factor. Recall that Noble (1981) required a change in both the charge radius and the magnetic moment. Any substantial change in the proton magnetic form factor is ruled out by small angle inclusive scattering at high $Q^2$, where magnetic scattering dominates. Despite the apparent suppression of the longitudinal response, other authors (Ulmer *et al* 1987, Blomqvist *et al* 1995, Dutta *et al* 2000) find no suppression on $^{12}$C for the p-wave nucleons. The more tightly bound s-wave nucleons overlap with the onset of multiparticle production, where an excess of transverse response is known to occur (see also Kelly (1996)).

Semi-inclusive quasielastic scattering has recently entered a new phase with the use of polarized beams and measurement of recoil proton polarization in the reaction $A(\vec{e}, e'\vec{p})(A-1)$. The advantage is that the ratio of the electric and magnetic responses is made at one set of kinematics, and the systematic errors associated with the Rosenbluth separation are avoided. Experiments have been performed at Jefferson Laboratory on $^{16}$O at $Q^2$ of 0.8 (GeV c$^{-1}$) $^2$ (Malov *et al* 2000) and at Mainz on $^{4}$He at $Q^2$ of 0.4 (GeV c$^{-2}$) (Dieterich *et al* 2001). The oxygen data agrees with the free proton form factor ratio with an uncertainty of about 18% and the authors make the wry comment 'reliable identification of changes of the form factor in the medium remains an ambitious undertaking'. The Mainz data is somewhat more precise; the ratio of $G_\mathrm{E}/G_\mathrm{M}$ on $^{4}$He and $^{2}$H is $0.88 \pm 0.04 \pm 0.01$. This result is clearly different from unity, but must be evaluated in terms of theoretical models before conclusions can be drawn on a modification of the form factor. There is also further data at higher $Q^2$ (Strauch *et al* 2002) which also favours a medium modification of the proton form factors in $^{4}$He. These results are claimed to favour models invoking quark–hadron duality and disfavour large in-medium modifications of the nucleon form factor (Melnitchouk *et al* 2002). However, it was mentioned above that medium modification is a controversial topic, and its opponents (Carlson *et al* 2003) claim that there may be inadequacies in the treatment of meson exchange currents and/or final state interactions.

A great deal of the current interest in $(e, e'p)$ reactions is in the transparency of the nuclear medium to the ejected proton: this is sufficiently removed from the original EMC effect that it will not be discussed further in this paper.

*7.1.3. y-scaling.* The properties of the nucleon within the nucleus can, it is claimed, be investigated through the phenomenon of $y$-scaling. In inclusive electron scattering at large enough three-momentum $|\boldsymbol{q}|$, the response, which in principle could depend on $|\boldsymbol{q}|$ and $\omega$, the energy transfer, depends only on the scaling variable $y$, where

$$y = \frac{\omega}{|\boldsymbol{q}|} - \frac{|\boldsymbol{q}|}{2M_\mathrm{N}} \tag{7.4}$$

where $M_\mathrm{N}$ is the free nucleon mass. $y$ is the momentum fraction of the struck nucleon parallel to the three-momentum transfer $|\boldsymbol{q}|$. This result is true for non-relativistic non-interacting particles (West 1975). It has been generalized to include relativistic effects (Sick *et al* 1980), nucleon binding and momentum (Ciofi degli Atti *et al* 1983, Ciofi degli Atti 1984, Cenni *et al* 1989, Yen *et al* 1989) and for final state interactions (Gurvitz and Rinat 1987). A specific and

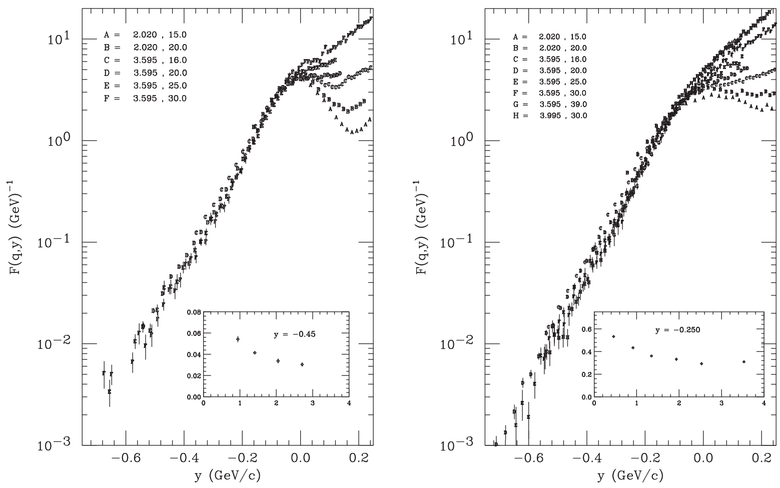


**Figure 18.** $y$-scaling curves for Day *et al* (1993) for $^4$He (left) and $^{56}$Fe (right).

revealing study has also been made of the relativistic Fermi gas model (Alberico *et al* 1988). A comprehensive survey can be found in Day *et al* (1990). It has even been generalized to the application of a single scaling function for all nuclei (Donnelly and Sick 1999a, b, Maieron *et al* 2002) for $A \geqslant 4$ by a function which is close to $y/k_{\mathrm{F}}$, with $k_{\mathrm{F}}$ the Fermi momentum.

The data for $^3$He (Sick *et al* 1980, Bosted *et al* 1982) show good evidence for scaling in the variable $y$ for $y < 0$. This has been used by Sick (1985) to set a limit of at most 6% in the change in the nucleon scale in $^3$He (or 3% if the size and inverse mass scale together). This analysis has been refined (McKeown 1986) to give a value of the ratio of the nucleon radius in $^3$He to that of the free nucleon of $1.025 \pm 0.011$, or an upper limit of 3.6%. However, $^3$He, on which most high $|\boldsymbol{q}|$ data is taken, is not very typical in its EMC effect; the dynamical rescaling model predicts only a 4% scale change (Close *et al* 1985a). For heavier nuclei, $^{40}$Ca shows goodish scaling at $y < 0$ if the nucleon mass and separation energy at low $q$ were allowed to vary (Zimmerman *et al* 1979), while at higher momentum transfer (Day *et al* 1987, 1993) on a series of nuclei ($^4$He, $^{12}$C, $^{27}$Al, $^{56}$Fe and $^{197}$Au) it has been shown that scaling is approached asymptotically as $|\boldsymbol{q}|$ increases (figure 18), the approach being slower for the heavier nuclei. This has been attributed to final state interactions: the recoiling nucleon is subject to FSI and influences the inclusive electron spectrum. The larger smearing in heavy nuclei may also lead to a contamination by other inelastic processes.

The data of Day *et al* (1993) extends up to $x = 1$ and beyond to $x > 2$, and the ratio between Fe and He shows a pattern suggestive of the presence of multiquark $(3, 6, 9, \ldots)$ states in this region, although the errors are too large to draw any firm conclusion. Such a contribution at a fixed value of $x$ would imply a violation of $y$-scaling (Day *et al* 1990), whereas $y$-scaling is approximately satisfied. Hence this cannot be regarded as evidence for multiquark clusters. More recent data (Arrington *et al* 1996, 1999, 2001), the last two named at Jefferson Laboratory, have also explored the region around $x = 1$. They find that the data scale in the Nachtmann variable $\xi$: this had already been seen by Filippone *et al* (1992). The scaling violation arising from the different dependence on $Q^2$ of the quasielastic scattering from the deep inelastic continuum is moderated by a shift in the scaling variable when $\xi$ is introduced. On the other hand, Benhar and Liuti (1995) regard the $\xi$ scaling as an accident. At large $Q^2$, $\xi$ can be expressed as a function only of $y$, and so scaling in $\xi$ and in $y$ can be compatible, although they are by no means equivalent. Unfortunately, the latest data, a factor of 100 more sensitive than Day *et al* (1993), tell us nothing about the region around $x = 2$, where crucial tests of the EMC effect and multiquark clusters could be made.

*7.1.4. Theoretical models.* In most models of the atomic nucleus, the constituent nucleons are bound by the exchange of mesons (chiefly $\sigma$, $\omega$, $\rho$ and $\pi$). In the isoscalar exchange, the scalar meson $\sigma$ binds the nucleons, while the vector meson $\omega$ provides a hard-core repulsion, preventing the nucleus collapsing. Various models build on this to calculate the change in nucleon properties inside the nucleus. A sample of such nuclear models is discussed here.

In a covariant non-topological soliton model for the nucleon, Celenza *et al* (1984, 1985a, b) have proposed that the quarks of the nucleon couple chiefly to $\omega$ and $\sigma$ mesons, and also to a scalar field $\chi$ which is related to the QCD vacuum and to confinement. The intense fields experienced by the soliton solution of the field equation modify its properties. The parameters of the $\chi$ meson are determined by fixing the masses of the exchanged mesons. The result is a change of all the nucleon parameters in the nucleus ($G_{\mathrm{E}}$, $\mu_{\mathrm{p}}$ and $G_{\mathrm{M}}$). The effective radius parameter in iron is larger by 15% than for a free nucleon. The increase of the magnetic radius seems to be at odds with data at high $Q^2$. The field $\chi$ itself has no physical basis. The authors also claim that the nuclear charge distribution in $^{208}$Pb can be better understood using medium-modified form factors (Celenza *et al* 1985c).

In the quark–meson coupling (QMC) model (Guichon 1988) the $\sigma$ and $\omega$ mesons couple directly to the quarks in the nucleon, which is described as an 'MIT bag'. Effects as large as 8% in the nucleon electric form factor at $Q^2$ of 0.3 GeV c$^{-2}$ are predicted (Lu *et al* 1998) while at the same time predicting a very small (1–2%) effect in the nucleon magnetic form factor, as required by experiment. Further studies at higher $Q^2$ (Lu *et al* 1999) suggest a rather complicated structure: the value of the bound nucleon magnetic moment $\mu$ is increased by about 8%, while the electric and magnetic form factors, relative to the free nucleon, first decrease as $Q^2$ increases, then increase at higher $Q^2$, with a minimum in $G_{\mathrm{E}}$ at around 1–1.5 GeV c$^{-2}$. Effects have also been predicted for different shell model nucleon levels. Such effects could be observable at current facilities. The same model has been applied (Saito *et al* 1999) to a calculation of the quenching of the longitudinal quasielastic response function and the Coulomb sum rule. An effect of 20% is obtained relative to the standard Hartree calculation.

In a chiral bag model for the nucleon, in which the quark core is surrounded by a non-perturbative meson cloud, it is argued (Brown and Rho 1989, Soyeur *et al* 1993) that the change in the exchanged vector meson mass causes a 'swelling' of the meson cloud, accounting for the missing longitudinal strength at low $Q^2$, whereas at higher $Q^2$ ($|\boldsymbol{q}| > \boldsymbol{m}^*_\omega$) the meson term becomes unimportant compared with the bag term and the strength is restored. This is required by the success of $y$-scaling. At the same time, the transverse response is relatively unchanged because the nucleon effective mass changes as well as the vector meson mass, and the net effects cancel.

## *7.2. Polarization transfer reactions*

It had long been suggested (Alberico *et al* 1982) that an enhancement of the pion field in the nucleus could be tested by polarization transfer reactions on nuclear targets using beams of polarized protons and measuring the scattered nucleon polarization. A measurement of the longitudinal to transverse response ratio for deuterium and lead was expected to show an enhancement in lead, a precursor of the transition to a pion condensate, but no such effect was seen (Carey *et al* 1984, Rees *et al* 1986) for detection of the recoil proton. There is also no enhancement of $R_{\mathrm{L}}/R_{\mathrm{T}}$ on carbon (Chan *et al* 1990). This need not be fatal for the pion model (Llewellyn Smith 1985, Esbensen *et al* 1985, Okuhara *et al* 1987) since the calculations assumed infinite nuclear matter without surface effects, ignored the spin-orbit effect in the incoming nucleon, which can mix and wash out the difference between longitudinal and transverse responses, and because the reaction is a mixture of isoscalar and isovector parts which can also dilute the effect. Distortion of the incoming wave can also modify the simple conclusion (Kawahigashi *et al* (2001) and references therein).

$(\vec{p}, \vec{n})$ reactions isolate the isovector response (McClelland *et al* 1992, Chen *et al* 1993, Alford and Spicer 1998). As for the proton recoil reaction, no enhancement in $R_{\mathrm{L}}/R_{\mathrm{T}}$ was seen. Theoretical attempts were made to reconcile these results. Horowitz and Piekarewicz (1994) advocated a reduction of the nucleon mass in the nuclear medium and as a consequence a suppression of the $\pi$NN coupling in the medium, the latter reducing the longitudinal response. Yoshida and Toki (1999) were able to reduce the effect in the longitudinal response by the use of pseudovector pion–nucleon coupling rather than the more conventional pseudoscalar. Brown and Wambach (1994) (see also Brown *et al* (1995)) achieved the required longitudinal–transverse ratio at a momentum transfer of $1.72\,\mathrm{fm}^{-1}$ by reducing the in-medium $\rho$ mass to 0.8 of its free space value, an effect they justify with respect to other processes. However, it is not clear that this balance would not be upset at other momentum transfers. Koltun (1998) argues that the effects calculated with conventional nuclear theory with a dominant effect from two-nucleon calculations do not agree with models based on the random phase approximation. Predicted effects in $R_{\mathrm{L}}/R_{\mathrm{T}}$ for the former are too small to measure. The same model reduces drastically the effect of excess pions on the structure functions of nuclei.

Further measurements (Taddeucci *et al* 1994, Wakasa *et al* 1999, Hautala *et al* 2002) were able to identify the responses $R_{\mathrm{L}}$ and $R_{\mathrm{T}}$ themselves and not just the ratios. The surprising result is that the longitudinal response $R_{\mathrm{L}}$ agrees with the theory, whereas the transverse response $R_{\mathrm{T}}$ is much larger than prediction and this is entirely unexplained.

### *7.3. Nuclear magnetic moments*

Nuclear magnetic moments may be calculated from single particle states in the shell model configuration of nuclei. It has been found that these moments are in some cases larger than expected, possibly implying an increase of the nucleon's magnetic moment inside a nucleus. These discrepancies can be described in conventional nuclear physics terms by meson-exchange currents, isobar effects, etc (e.g. Ericson and Richter (1987), Castel and Towner (1990)). A more radical approach (Karl *et al* 1984) is to use a hybrid six-quark bag model in which nucleons retain their separate identities at separations $r$ of 1 fm but coalesce into six-quark bags for $r < r_0$. The effective magnetic moment of the $6q$ bag is increased since the bag size is assumed to be larger than that of a $3q$ bag and the magnetic moment of each quark is proportional to the bag radius. For $^3$H and $^3$He, the authors use a nucleon–dinucleon probability of 25% to generate changes in the moments of the correct sign and magnitude. While the model is most interesting, it has difficulties (Arima 1985). It predicts changes $\delta\mu$ of the form $\delta\mu\ (^3\mathrm{H}) \simeq -\frac{3}{2}\delta\mu\ (^3\mathrm{He})$ whereas the experimental shifts are much closer to $\delta\mu(^3\mathrm{He})$. It would give rise to larger, unobserved effects in heavier odd-$A$ nuclei, and the 25% probability for the $6q$ configuration is very high, implying an 11% scale change and inconsistent with $y$-scaling on $^3$He as discussed above (Sick 1985). Therefore one is tempted to assume that only part of the enhancement is due to six-quark effects.

Other work on these lines has been done on the deuteron (Bhaduri and Nogami 1985). Using the method of Karl *et al* they note that the deuteron magnetic moment is given conventionally by $\mu_{\mathrm{D}} = 0.8797–0.570P_{\mathrm{D}}$ where $P_{\mathrm{D}}$ is the $D$-state admixture in the deuteron, which reduces the magnetic moment from its free nucleon value. This implies a $D$-state admixture of 4%, whereas nucleon–nucleon potentials demand 6–7%. The discrepancy, while usually ascribed to meson exchange currents, can also be resolved by the addition of a $6q$ state with probability in the range 3.6–5.3%, using a cutoff radius of 1 fm. This magnitude is not unreasonable.

Finally, evidence has been presented for enhancements of the nuclear magnetism in heavy nuclei (Yamazaki 1985) of $8 \pm 3\%$ for $^{208}$Pb, from a study of effective orbital $g$-factors (as opposed to the spin $g$-factors for $^3$H and $^3$He). The effects of meson exchange currents and nuclear core polarization have been separated out. The value is somewhat small for Pb but results from a complex interplay between different effects and must be difficult to calculate with complete reliability. A less precise measurement of the orbital $g$-factor for neutrons (Beck *et al* 1987) does not support such an increase.

### 7.4. Quenching of nuclear transitions

It has been known for some considerable time (Wilkinson 1973) that the Gamow–Teller $\beta$ decays of mirror nuclei proceed more slowly than expected. Indeed, the free space value of $g_A/g_V$ (1.26) seems to be reduced to around unity in nuclear transitions (Buck and Perez 1983, Buck *et al* 2001). This seems to be accepted by many authors (e.g. Park *et al* (1997), Carter and Prakash (2002)), but has been disputed. Birse and Miller (1984), Delorme (1985) and Close *et al* (1988) have argued that too much information is being extracted from too little data, and that pion effects and the potential change of magnetic $g$-factors are not taken into account. In the dynamical rescaling model it would be preferred that $g_A/g_V$ would be unchanged in going from a nucleon to a nucleus (Close *et al* 1988). Kaptari and Umnikov (1990) attribute the discrepancy to the omission of non-nucleonic degrees of freedom such as $\pi$, $\Delta$ and $6q$ bags.

In addition to this, certain isovector Ml transitions in nuclei (related to Gamow–Teller decays by isospin rotation) are also quenched (Bertozzi *et al* 1982), as are the sum-rule strengths of excitation of Gamow–Teller resonances (Goodman 1984).

This would seem to represent a possible change in the properties of the nucleon when in a nucleus. It has been traditionally and successfully (Towner 1986) described in a complete but complicated model including, in particular, the virtual excitation of $\Delta$ resonances. However, a parallel explanation may lie in a model more reminiscent of the EMC effect. The presence of six-quark bags in nuclei can result in the reduction of $g_A$ (Rho 1984) with a $6q$ probability of 30% necessary to reduce $g_A$ to 1 in nuclei. An alternative but complementary approach (Rho 1985) regards the renormalization of $g_A$ as a medium-induced effect arising from an increase in the size of the confining bag by up to 40%.

These effects have been linked with a possible partial restoration of chiral symmetry in nuclei (e.g. Birse (1994)).

### 7.5. $K^+$ nucleus scattering

$K^+$-nucleon scattering at low momenta ($<800\,\mathrm{MeV\,c^{-1}}$) is predominantly s-wave, and the elastic scattering phase shift varies linearly with the cm momentum. This behaviour can be realized in a simple hard-sphere model with radius 0.32 fm. An interesting observation (Siegel *et al* 1985) is that the differential $K^+$-nucleus elastic scattering cross-sections on $^{12}$C and $^{40}$Ca (Marlow *et al* 1982) do seem to require an increase in the $S_{11}$ phase shift by 10–20% compared with free nucleon phase shifts, but others (Peterson 1999) require higher values. This increase would be consistent with an increase in 'size' or confinement radius of 10–30% for a nucleon in a nucleus. Further data on other nuclei (Sawafta *et al* 1993) confirm the effect. These measurements are susceptible to normalization errors and may be less reliable for heavier nuclei (Arima and Masutani 1993). There may be errors in the free nucleon phase shifts, and a cleaner test comes from a direct comparison of the $K^+$ total cross-sections on carbon and deuterium using data taken at Nimrod over 30 years ago (Bugg *et al* 1968) and again at Brookhaven (Mardor *et al* 1990, Krauss *et al* 1992). Many experimental uncertainties cancel in this ratio, and the result again implies a 10–20% change in the phase shift. While this is a very interesting result, and which should generate more experimental data, the 'radius' of 0.32 fm which is varying is much smaller than confinement radii discussed in other contexts, and this difference should be better understood. Indeed, the result has been interpreted without any nucleon swelling but invoking a density dependence of the vector meson masses which mediate the $K^+N$ interaction (Brown *et al* 1988). Attempts to explain the excess $K^+N$ cross-section by means of extra pions (Akulinichev 1992, Jiang and Koltun 1992) rather than by a swelling of the nucleon have been criticized (Miller 1992) on the grounds that the average number of pions per nucleon used, 0.07, is too large by a factor of 2 compared with current limits.

## 8. Summary and conclusions

The EMC effect has been with us for 20 years, and the idea that the quark distributions in nucleons are modified in nuclei is now part of standard textbook physics. During this time no single explanation for the effect has been forthcoming. While the data has now converged to a uniform picture, the HERMES effect having been withdrawn, the models listed above all have something to contribute to the phenomenology. Each has been developed to make predictions for as yet unobserved or very limited data such as an EMC effect for gluons or sea quarks, and can be tested against any new results.

What seems to be a common feature in the 'EMC effect' region between $x$ of 0.3 and 0.7 is that there appears to be a single change of scale. Whether this results from a rescaling in $x$ such as in the binding, cluster and pion models or in $Q^2$ in the dynamical rescaling model, the basic behaviour in the data is reproduced by such a single scale change. This feature is shared by most if not all of the models considered. However, the 'derivation' of this scale change is where opinions differ. Since the overall behaviour in this region is similar in all models, they may be different ways of looking at the same thing. However, multi-body physics is complex, and for now we have to look at the models separately. There remains controversy about the precise parameters used for the binding model, although it must surely be an ingredient in any explanation. The nucleon separation energy, a vital ingredient in the calculation, should not be varied at will, but a consensus should be reached before detailed comparisons with data are made. The pion model drew much from the early, superseded data which showed the ratio rising steeply at small $x$, and more recently showed an apparent crisis (Bertsch *et al* 1993) in its inability to explain convincingly Drell–Yan data and polarization transfer. However, the Drell–Yan data ratios agree with the deep inelastic scattering ratios when valence and sea components in the latter are allowed for, and shadowing may mask pionic effects. It is important to determine whether the sea quark distribution shows shadowing. Multiquark clusters can help to explain some of the experimental observations, while remaining rather *ad hoc*. What is needed is clear and unambiguous evidence of multiquark clusters to make the model more credible. The ambitious goals of dynamical rescaling seem to have quite close resemblance to data, and the approach has an obvious appeal, while lacking some fundamental justification. Its limited range of applicability in $x$ is a drawback, although in the intermediate $x$ range it gives the best account of the data.

Changes in physical size of nucleons in nuclei of up to 30% had been a feature of some of the early models. While some changes are expected, and indeed possibly seen, large scale changes seem to be ruled out by electron scattering data and nuclear moments. Whether there is any change at all in nucleon properties in nuclei remains controversial.

The broad picture of a lack of $Q^2$-dependence in the data seems to be in accord with studies of QCD evolution. While the experimental effect associated with valence quarks seems to be agreed, the same cannot be said for the sea or the gluon distribution, where more data is needed, particularly at very low $x$, to check the shadowing behaviour of each.

More experimental data is therefore needed to clarify a number of outstanding issues: the gluon distribution in nuclei relative to nucleons is poorly known and then only in a limited $x$ range. Further data is required on $J/\psi$ and open charm production, both of which are assumed to proceed via the photon–gluon fusion process, and where the latter is probably more model-independent and capable of covering a wider $x$ range. Relative gluon densities can also be obtained (Gousset and Pirner 1996) from logarithmic scaling violation in the structure function ratio. This can only be improved with higher precision data, ideally over a wider $x$ range. When the current round of experiments is complete, a further development could come from high energy electron–ion colliders, and many studies have been made of the physics potential of such a machine (Holt *et al* 2002).

The separation of the EMC effect into its valence and sea quark components is very primitive and model dependent at present, unless factorization holds exactly and Drell–Yan cross-sections reveal the antiquark distributions of deep inelastic scattering. Even then, Drell–Yan data is probably at its limit without higher luminosity and higher energy fixed target data. Neutrino and antineutrino scattering offer a direct separation between valence and sea distributions; current data have very poor statistics, but immense potential is provided by neutrino factories (e.g. Edgecock and Murray (2001)) where an intense beam of neutrinos is produced from muons in a storage ring and directed at a detector at a fairly close distance. Although this would not be able to explore very low $x < 0.02$ because of the energy limit of the neutrinos, there would be great value in this measurement, even if it is some years away.

Shadowing is still lacking complete clarification in its $Q^2$ and $x$ dependence and more data is needed at higher $Q^2$ at low $x$. This can only be achieved by increasing the beam energy in a fixed target experiment, or, more promisingly, by the use of an electron–ion collider which would provide a much higher centre of mass energy.

Despite the lack of success in coming to a universal understanding of the data, it is reassuring for the health of future studies to encounter papers entitled '*The return of the EMC effect*' (Miller and Smith 2002, Smith and Miller 2002) in which the work continues: a case is made for other effects beyond the meson plus nucleon model.

## Acknowledgments

I would like to express my gratitude to a large number of people: on the experimental side to Terry Sloan and Klaus Rith in particular; on the theory side I have been privileged to have many contacts with Frank Close, Dick Roberts and Graham Ross, although I do not always agree with them. I also acknowledge conversations with Mark Strikman and Tony Thomas, a very useful correspondence with Steve Rock, and information from Dirk Ryckbosch on the HERMES data. I thank Bill Scott for a careful reading of the final draft, and finally, but by no means least, I thank Erwin Gabathuler, the founding father of EMC.

## References

Ableev V G *et al* 1983 *JETP Lett.* **37** 233
Abramowicz H *et al* 1984 *Z. Phys.* C **25** 29

Abreu M C *et al* 2000 *Phys. Lett.* B **477** 28
Ackerstaff K *et al* 2000 *Phys. Lett.* B **475** 386
Adams M R *et al* 1992a *Phys. Rev. Lett.* **68** 3266
——1992b *Phys. Lett.* B **287** 375
——1995 *Z. Phys.* C **67** 403
Airapetian A *et al* 2002a *DESY Preprint* DESY 02-092
——2002b DESY *Preprint* DESY 02-091
Åkesson T *et al* 1982 *Nucl. Phys.* B **209** 309
Akulinichev S V 1992 *Phys. Rev. Lett.* **68** 290
Akulinichev S V and Shlomo S 1990 *Phys. Lett.* B **234** 170
Akulinichev S V *et al* 1985a *JETP Lett.* **42** 127
——1985b *Phys. Lett.* B **158** 485
——1985c *Phys. Rev. Lett.* **55** 2239
——1985d *J. Phys. G: Nucl. Part. Phys.* **11** L245
Alberico W M *et al* 1982 *Nucl. Phys.* A **379** 429
——1988 *Phys. Rev.* C **38** 1801
Alde D M *et al* 1990 *Phys. Rev. Lett.* **64** 2479
Alford W P and Spicer B M 1998 *Adv. Nucl. Phys.* **24** 1
Allasia D *et al* 1991 *Phys. Lett.* B **258** 493
Altarelli G and Parisi G 1977 *Nucl. Phys.* B **126** 298
Altemus R *et al* 1980 *Phys. Rev. Lett.* **44** 965
Alverson G *et al* 1993 *Phys. Rev.* D **48** 5
Amaudruz P *et al* 1991 *Z. Phys.* C **51** 387
——1992a *Z. Phys.* C **53** 73
——1992b *Phys. Lett.* B **294** 120
——1992c *Nucl. Phys.* B **371** 553
——1995 *Nucl. Phys.* B **441** 3
Ammosov V V *et al* 1984 *JETP Lett.* **39** 393
Angelini C and Pazzi R 1985 *Phys. Lett.* B **154** 328
Angelis A L S *et al* 1982 *Phys. Lett.* B **116** 379
Antonov A N *et al* 1991 *Nuovo Cimento* A **104** 487
Antreasyan D *et al* 1979 *Phys. Rev.* D **19** 764
Apanasevich L *et al* 1999 *Phys. Rev.* D **59** 074007
——2001 *Phys. Rev.* D **63** 014009
Arima A 1985 *Nucl. Phys.* A **446** 45c
Arima M and Masutani K 1993 *Phys. Rev.* C **47** 1325
Arneodo M 1994 *Phys. Rep.* **240** 301
Arneodo M *et al* 1988 *Phys. Lett.* B **211** 493
——1990 *Nucl. Phys.* B **333** 1
——1995 *Nucl. Phys.* B **441** 12
——1996a *Nucl. Phys.* B **481** 3
——1996b *Nucl. Phys.* B **481** 23
Arnold R G *et al* 1975 *Phys. Rev. Lett.* **35** 776
——1984 *Phys. Rev. Lett.* **52** 727
Arrington J *et al* 1996 *Phys. Rev.* C **53** 2248
——1999 *Phys. Rev. Lett.* **82** 2056
——2001 *Phys. Rev.* C **64** 014602
Ashman J G *et al* 1988 *Phys. Lett.* B **202** 603
——1992 *Z. Phys.* C **56** 21
——1993 *Z. Phys.* C **57** 211
Asratyan A E *et al* 1985 *Sov. J. Nucl. Phys.* **41** 763
——1986 *Sov. J. Nucl. Phys.* **43** 380
Aubert J J *et al* 1983a *Phys. Lett.* B **123** 123
——1983b *Phys. Lett.* B **123** 275
——1983c *Nucl. Phys.* B **213** 1
——1985 *Nucl. Phys.* B **259** 189
——1986 *Nucl. Phys.* B **272** 158
——1987 *Nucl. Phys.* B **293** 740

Baglin C *et al* 1991 *Phys. Lett.* B **270** 105
Bailey J *et al* 1979 *Nucl. Phys.* B **151** 367
Baldin A M *et al* 1974 *Sov. J. Nucl. Phys.* **18** 41
Baldin A M 1985 *Nucl. Phys.* A **447** 203c
Ballocchi G and Zieliński M 1986 *Z. Phys.* C **32** 27
Baran D T *et al* 1988 *Phys. Rev. Lett.* **61** 400
Bari G *et al* 1985 *Phys. Lett.* B **163** 282
Barreau P *et al* 1983 *Nucl. Phys.* A **402** 515
Barshay S 1985 *Z. Phys.* C **27** 443
Bauer T H *et al* 1978 *Rev. Mod. Phys.* **50** 261
Baym G 1979 *Physica* A **96** 131
Beck R *et al* 1987 *Phys. Rev. Lett.* **59** 2923
Benhar O and Liuti S 1995 *Phys. Lett.* B **358** 173
Benhar O *et al* 1997 *Phys. Lett.* B **410** 79
Benvenuti A C *et al* 1987 *Phys. Lett.* B **189** 483
——1989 *Phys. Lett.* B **223** 485
Berger E L and Jones D 1981 *Phys. Rev.* D **23** 1521
Berger E L and Coester F 1985 *Phys. Rev.* D **32** 1071
Berger E L *et al* 1984 *Phys. Rev.* D **29** 398
Berger E L 1986 *Nucl. Phys.* B **267** 231
Berger E L and Qiu J 1988 *Phys. Lett.* B **206** 141
Bertozzi W 1982 *Nucl. Phys.* A **374** 109c
Bertsch G F *et al* 1993 *Science* **259** 773
Bhaduri R K and Nogami Y 1985 *Phys. Lett.* B **152** 35
Bickerstaff R P *et al* 1984 *Phys. Rev. Lett.* **53** 2532
——1985 *Phys. Lett.* B **161** 393
——1986 *Phys. Rev.* D **33** 3228
Bickerstaff R P and Miller G A 1986a *Phys. Lett.* B **168** 409
——1986b *Phys. Rev.* D **34** 2890
Bickerstaff R P and Thomas A W 1987 *Phys. Rev.* D **35** 108
——1989 *J. Phys. G: Nucl. Part. Phys.* **15** 1523
Bilchak C L *et al* 1988 *Phys. Lett.* B **214** 441
Birbrair B L *et al* 1986 *Phys. Lett.* B **166** 119
——1989a *Phys. Lett.* B **222** 281
——1989b *Nucl. Phys.* A **491** 618
Birse M C 1994 *J. Phys. G: Nucl. Part. Phys.* **20** 1537
Birse M C and Miller G A 1984 *Phys. Rev. Lett.* **52** 1838
Blancenbecler R and Brodsky S J 1974 *Phys. Rev.* D **10** 2973
Blatchley C C *et al* 1986 *Phys. Rev.* C **34** 1243
Blomqvist K I *et al* 1995 *Z. Phys.* A **351** 353
Bloom E D *et al* 1969 *Phys. Rev. Lett.* **23** 930
Bodek A and Ritchie J L 1981 *Phys. Rev.* D **23** 1070
Bodek A and Simon A 1985 *Z. Phys.* C **29** 231
Bodek A *et al* 1983a *Phys. Rev. Lett.* **50** 1431
——1983b *Phys. Rev. Lett.* **51** 534
Boffi S *et al* 1996 *Electromagnetic Response of Atomic Nuclei* (Oxford: Oxford University Press) pp 145–6
Bordalo P *et al* 1987 *Phys. Lett.* B **193** 368
Bosted P *et al* 1982 *Phys. Rev. Lett.* **49** 1380
Bräuer K *et al* 1985 *Nucl. Phys.* A **437** 717
Brodsky S J *et al* 2002 *Phys. Rev.* D **65** 114025
Bromberg C *et al* 1979 *Phys. Rev. Lett.* **42** 1202
Brown G E *et al* 1988 *Phys. Rev. Lett.* **60** 2723
——1995 *Nucl. Phys.* A **593** 295
Brown G E and Rho M 1989 *Phys. Lett.* B **222** 324
Brown G E and Wambach J 1994 *Nucl. Phys.* A **568** 895
Buck B and Perez S M 1983 *Phys. Rev. Lett.* **50** 1975
Buck B *et al* 2001 *Phys. Rev.* C **63** 037301
Bugg D V *et al* 1968 *Phys. Rev.* **168** 1466

Burkardt M and Miller G A 1998 *Phys. Rev.* C **58** 2450
Burov V V *et al* 1982 *Z. Phys.* A **306** 149
——1984 *Z. Phys.* A **318** 67
Bystritsky V M *et al* 2001 *JETP Lett.* **73** 453
Caldwell D O *et al* 1979 *Phys. Rev. Lett.* **42** 553
Carey T A *et al* 1984 *Phys. Rev. Lett.* **53** 144
Carlson C E and Havens T J 1983 *Phys. Rev. Lett.* **51** 261
Carlson J *et al* 2003 *Phys. Lett.* B **553** 191
Carter G W and Prakash M 2002 *Phys. Lett.* B **525** 249
Castel B and Towner I S 1990 *Modern Theories of Nuclear Moments* (Oxford: Clarendon) pp 1–34
Celenza L S *et al* 1984 *Phys. Rev. Lett.* **53** 892
——1985a *Phys. Rev.* C **31** 212
——1985b *Phys. Rev.* C **31** 232
——1985c *Phys. Rev.* C **31** 1944
Cenni R *et al* 1989 *Phys. Rev.* C **39** 1425
Chan C *et al* 1990 *Nucl. Phys.* A **510** 713
Chanfray G *et al* 1984 *Phys. Lett.* B **147** 249
Chemtob M and Peschanski R 1984 *J. Phys. G: Nucl. Part. Phys.* **10** 599
Chen J P *et al* 1991 *Phys. Rev. Lett.* **66** 1283
Chen X Y *et al* 1993 *Phys. Rev.* C **47** 2159
Chmaj T and Heller K 1984 *Acta Phys. Polonica* B **15** 473
——1985 *Lett. Nuov. Cim.* **42** 415
Ciofi degli Atti 1984 *Lett. Nuov. Cim.* **41** 161
Ciofi degli Atti C and Liuti S 1989 *Phys. Lett.* B **225** 215
——1991 *Phys. Rev.* C **44** 1269
Ciofi degli Atti C *et al* 1983 *Phys. Lett.* B **127** 303
Clark B C *et al* 1985 *Phys. Rev.* D **31** 617
Cleymans J and Thews R L 1985 *Phys. Rev.* D **31** 1014
Close F E 1979 *An Introduction to Quarks and Partons* (London: Academic)
Close F E *et al* 1983 *Phys. Lett.* B **129** 346
——1984 *Phys. Lett.* B **142** 202
——1985a *Phys. Rev.* D **31** 1004
——1985b *Z. Phys.* C **26** 515
——1986 *Phys. Lett.* B **168** 400
——1988 *Nucl. Phys.* B **296** 582
——1989 *Phys. Rev.* D **40** 2820
Close F E and Roberts R G 1988 *Phys. Lett.* B **213** 91
Cooper A M *et al* 1984 *Phys. Lett.* B **141** 133
Corcoran M D *et al* 1991 *Phys. Lett.* B **259** 209
Cronin J W *et al* 1975 *Phys. Rev.* D **11** 3105
Dasu S *et al* 1988 *Phys. Rev. Lett.* **60** 2591
——1994 *Phys. Rev.* D **49** 5641
Daté S 1983 *Prog. Theor. Phys.* **70** 1682
Day D B *et al* 1987 *Phys. Rev. Lett.* **59** 427
——1990 *Ann. Rev. Nucl. Part. Sci.* **40** 357
——1993 *Phys. Rev.* C **48** 1849
Deady *et al* 1983 *Phys. Rev.* C **28** 631
——1986 *Phys. Rev.* C **33** 1897
Deden H *et al* 1975 *Nucl. Phys.* B **85** 269
de Florian D *et al* 1994 *Z. Phys.* A **350** 55
deForest T Jr and Walecka J D 1966 *Adv. Phys.* **15** 1
Delorme J 1985 *Nucl. Phys.* A **446** 65c
Dias de Deus J *et al* 1984a *Z. Phys.* C **26** 109
——1984b *Phys. Rev.* D **30** 697
Dieperink A E L and Miller G A 1991 *Phys. Rev.* C **44** 866
Dieperink A E L and Korpa C L 1997 *Phys. Rev.* C **55** 2665
Dieterich S *et al* 2001 *Phys. Lett.* B **500** 47
Donnelly T W and Sick I 1999a *Phys. Rev. Lett.* **82** 3212

——1999b *Phys. Rev.* C **60** 065502
Dorkin S M *et al* 1984 *Z. Phys.* A **316** 331
Dow K *et al* 1988 *Phys. Rev. Lett.* **61** 1706
Drell S D and Yan T M 1970 *Phys. Rev. Lett.* **25** 316
Ducret J E *et al* 1993a *Nucl. Phys.* A **553** 697c
——1993b *Nucl. Phys.* A **556** 373
Dunne G V and Thomas A W 1986a *Phys. Rev.* D **33** 2061
——1986b *Nucl. Phys.* A **455** 701
Dunne J A 2002 *Nucl. Phys.* A **699** 294c
Dutta D *et al* 2000 *Phys. Rev.* C **61** 061602(R)
Dytman S A *et al* 1988 *Phys. Rev.* C **38** 800
Edgecock T R and Murray W J 2001 *J. Phys. G: Nucl. Part. Phys.* **27** R141
Ericson M and Thomas A W 1983 *Phys. Lett.* **128**B 112
Ericson M and Rosa-Clot M 1987 *Phys. Lett.* B **188** 11
Ericson T E O and Richter A 1987 *Phys. Lett.* B **183** 249
Esbensen H *et al* 1985 *Phys. Rev.* C **31** 1816
Eskola K J *et al* 1998 *Nucl. Phys.* B **535** 351
——1999 *Eur. J. Phys.* C **9** 61
Faissner H and Kim B R 1983 *Phys. Lett.* B **130** 321
Faissner H *et al* 1984 *Phys. Rev.* D **30** 900
——1985 *Phys. Rev. Lett.* **54** 1902
Farrar G R and Jackson D R 1975 *Phys. Rev. Lett.* **35** 1416
Feynman R P 1972 *Photon–Hadron Interactions* (Reading, MA: Benjamin)
Filippone B W *et al* 1992 *Phys. Rev.* C **45** 1582
Frankfurt L L and Strikman M I 1981 *Phys. Rep.* **76** 215
——1987 *Phys. Lett.* B **183** 254
——1988 *Phys. Rep.* **160** 235
Fredriksson S 1984 *Phys. Rev. Lett.* **52** 724
Friman B L *et al* 1983 *Phys. Rev. Lett.* **51** 763
Frullani S and Mougey J 1984 *Adv. Nucl. Phys.* **14** 1
Gabellini Y *et al* 1985 *Z. Phys.* C **28** 123
Garcia Canal C A *et al* 1984 *Phys. Rev. Lett.* **53** 1430
Garsevanishvili V R and Menteshashvili Z R 1984 *JETP Lett.* **40** 1165
Garsevanishvili V R *et al* 1989 *Acta Phys. Polonica* B **20** 211
Geesaman D F *et al* 1995 *Ann. Rev. Nucl. Part. Sci.* **45** 337
Głazek S and Schaden M 1986 *Z. Phys.* A **323** 451
Godbole R M and Gupta S 1989 *Phys. Lett.* B **228** 129
Goldman T and Stephenson G J 1984 *Phys. Lett.* B **146** 143
Gomez J *et al* 1994 *Phys. Rev.* D **49** 4348
Goodman C D 1984 *Prog. Part. Nucl. Phys.* **11** 475
Goodman M S *et al* 1981 *Phys. Rev. Lett.* **47** 293
Gousset T and Pirner H J 1996 *Phys. Lett.* B **375** 349
Gross F and Liuti S 1992 *Phys. Rev.* C **45** 1374
Guèye P *et al* 1999 *Phys. Rev.* C **60** 044308
Guichon P A M 1988 *Phys. Lett.* B **200** 235
Guo X and Qiu J 1996 *Phys. Rev.* D **53** 6144
Gupta S 1985 *Pramāna* **24** 443
Gupta S and Sarma K V L 1985 *Z. Phys.* C **29** 329
Gupta S and Godbole R M 1986a *Z. Phys.* C **31** 475
——1986b *Phys. Rev.* D **33** 3453
Gupta S and Sridhar K 1987 *Phys. Lett.* B **197** 259
Gupta S *et al* 1985 *Z. Phys.* C **28** 483
Gurvitz S A and Rinat A S 1987 *Phys. Rev.* C **35** 696
Guy J *et al* 1987 *Z. Phys.* C **36** 337
——1989 *Phys. Lett.* B **229** 421
Hanlon J *et al* 1985 *Phys. Rev.* D **32** 2441
Hautala C *et al* 2002 *Phys. Rev.* C **65** 034612
Heller K J and Szwed J 1985 *Acta Phys. Polonica* B **16** 157

Hendry A W *et al* 1984 *Phys. Lett.* B **136** 433
——1986 *Nuovo Cimento* A **92** 427
Holt R *et al* 2002 *Brookhaven Preprint* BNL-68933
Hoodbhoy P and Jaffe R L 1987 *Phys. Rev.* D **35** 113
Horowitz C J and Piekarewicz J 1994 *Phys. Rev.* C **50** 2540
Hotta A *et al* 1984 *Phys. Rev.* C **30** 87
Hirai M *et al* 2001 *Phys. Rev.* D **64** 034003
Hsiung Y B *et al* 1985 *Phys. Rev. Lett.* **55** 457
Hwang W Y P *et al* 1988 *Phys. Rev.* D **38** 2785
Ishii C *et al* 1989 *Phys. Lett.* B **216** 409
Jaffe R L 1983 *Phys. Rev. Lett.* **50** 228
——1984 *Comments Nucl. Part. Phys* **13** 39
——1988 *Nucl. Phys.* A **478** 3c
Jaffe R L *et al* 1984 *Phys. Lett.* B **134** 449
Jalilian-Marian J *et al* 2002 *Nucl. Phys.* A **700** 523
Jändel M and Peters G 1984 *Phys. Rev.* D **30** 1117
Jiang M F and Koltun D S 1992 *Phys. Rev.* C **46** 2462
Johnson M B *et al* 2002 *Phys. Rev.* C **65** 025203
Jourdan J 1995 *Phys. Lett.* B **353** 189
——1996 *Nucl. Phys.* A **603** 117
Jung H and Miller G A 1988 *Phys. Lett.* B **200** 351
——1990 *Phys. Rev.* C **41** 659
Kalashnikova Y S *et al* 1986 *Z. Phys.* A **323** 205
Kaptari L P and Umnikov A Y 1990 *Phys. Lett.* B **240** 203
Karl G *et al* 1984 *Phys. Lett.* B **143** 326
Kawahigashi K *et al* 2001 *Phys. Rev.* C **63** 044609
Kelly J J 1996 *Adv. Nucl. Phys.* **23** 75
Kharzeev D *et al* 1999 *Eur. J. Phys.* C **9** 459
Kharzeev D and Satz H 1994 *Phys. Lett.* B **327** 361
Kisslinger L S 1982 *Phys. Lett.* B **112** 307
Kitagaki T *et al* 1988 *Phys. Lett.* B **214** 281
Koltun D S 1972 *Phys. Rev. Lett.* **28** 182
——1998 *Phys. Rev.* C **57** 1210
Kondratyuk L A and Shmatikov M Z 1984 *JETP Lett.* **39** 389
——1985 *Z. Phys.* A **321** 301
Krämer M 1996 *Nucl. Phys.* B **459** 3
Krauss R A *et al* 1992 *Phys. Rev.* C **46** 655
Krzywicki A 1976 *Phys. Rev.* D **14** 152
Krzywicki A *et al* 1979 *Phys. Lett.* B **85** 407
Kubar J *et al* 1984 *Z. Phys.* C **23** 195
Kulagin S A 1989 *Nucl. Phys.* A **500** 653
Kumano S and Close F E 1990 *Phys. Rev.* C **41** 1855
Lassila K E and Sukhatme U P 1988 *Phys. Lett.* B **209** 343
Lassila K E *et al* 1991 *Phys. Rev.* C **44** 1188
Leader E and Predazzi E 1996 *An Introduction to Gauge Theories and Modern Particle Physics* (2 vols) (Cambridge: Cambridge University Press)
Leitch M J *et al* 1995 *Phys. Rev.* D **52** 4251
——2000 *Phys. Rev. Lett.* **84** 3256
Lev M and Petersson B 1983 *Z. Phys.* C **21** 155
Li G L *et al* 1988 *Phys. Lett.* B **213** 531
Llewellyn Smith C H 1983 *Phys. Lett.* B **128** 107
——1985 *Nucl. Phys.* A **434** 35c
Lu D H *et al* 1998 *Phys. Lett.* B **417** 217
——1999 *Phys. Rev.* C **60** 068201
Maieron C *et al* 2002 *Phys. Rev.* C **65** 025502
Malov S *et al* 2000 *Phys. Rev.* C **62** 057302
Marchand C *et al* 1985 *Phys. Lett.* B **153** 29
Marco E *et al* 1996 *Nucl. Phys.* A **611** 484

Mardor Y *et al* 1990 *Phys. Rev. Lett.* **65** 2110
Marlow D *et al* 1982 *Phys. Rev.* C **25** 2619
Martin A D *et al* 1987 *Phys. Lett.* B **191** 200
Mathieu P and Watson P J S 1984 *Phys. Lett.* B **148** 473
Matsui T and Satz H 1986 *Phys. Lett.* B **178** 416
Matveev R G and Sorba P 1977 *Lett. Nuovo Cimento* **20** 435
McClelland J B *et al* 1992 *Phys. Rev. Lett.* **69** 582
McGaughey P L *et al* 1999 *Ann. Rev. Nucl. Part. Sci.* **49** 217
McKeown R D 1986 *Phys. Rev. Lett.* **56** 1452
Melnitchouk W *et al* 1992 *Z. Phys.* A **342** 215
——2002 *Eur. J. Phys.* A **14** 105
Meziani Z E *et al* 1984 *Phys. Rev. Lett.* **52** 2130
——1992 *Phys. Rev. Lett.* **69** 41
Migdal A B 1987 *Prog. Theor. Phys. Supp.* **91** 244
Migdal A B *et al* 1990 *Phys. Rep.* **192** 179
Miller G A 1992 *Phys. Rev. Lett.* **69** 2449
——2001 *Phys. Rev.* C **64** 022201
Miller G A and Smith J R 2002 *Phys. Rev.* C **65** 015211
Moniz E J 1969 *Phys. Rev.* **184** 1154
Moniz E J *et al* 1971 *Phys. Rev. Lett.* **26** 445
Morgenstern J and Meziani Z E 2001 *Phys. Lett.* B **515** 269
Morley P D and Schmidt I 1986 *Phys. Rev.* D **34** 1305
Morris C L *et al* 1998 *Phys. Lett.* B **419** 25
Mueller A H and Qiu J 1986 *Nucl. Phys.* B **268** 427
Mulders P J 1985 *Phys. Rev. Lett.* **54** 2560
——1990 *Phys. Rep.* **185** 83
Mulders P J and Thomas A W 1984 *Phys. Rev. Lett.* **52** 1199
Nachtmann O and Pirner H J 1984 *Z. Phys.* C **21** 277
Nakano K and Rafelski J 1987 *Phys. Rev.* C **36** 1497
Nikolaev N N and Zacharov V I 1975 *Phys. Lett.* B **55** 397
Nikolaev N N and Zacharov B G 1991 *Phys. Lett.* B **260** 414
Noble J V 1981 *Phys. Rev. Lett.* **46** 412
——1983 *Phys. Rev.* C **27** 423
Okuhara Y *et al* 1987 *Phys. Lett.* B **186** 113
Park T S *et al* 1997 *Phys. Lett.* B **409** 26
Parker M A *et al* 1984 *Nucl. Phys.* B **232** 1
Pasyuk E A *et al* 2001 *Phys. Lett.* B **523** 1
Peigné S 2002 *Phys. Rev.* D **66** 114011
Peterson R J 1999 *Phys. Rev.* C **60** 022201
Piller G and Weise W 2000 *Phys. Rep.* **330** 1
Piller G *et al* 1995 *Z. Phys.* A **352** 427
Pirner H J 1984 *Comm. Nucl. Part. Phys.* **12** 199
Pirner H J and Vary J P 1981 *Phys. Rev. Lett.* **46** 1376
Qiu J 1987 *Nucl. Phys.* B **291** 746
Rees L B *et al* 1986 *Phys. Rev.* C **34** 627
Reffay-Pikeroen D *et al* 1988 *Phys. Rev. Lett.* **60** 776
Rho M 1984 *Ann. Rev. Nucl. Part. Sci.* **34** 531
——1985 *Phys. Rev. Lett.* **54** 767
Rock S and Bosted P 2001 *Phys. Lett.* B **518** 34
Rosenfelder R 1980 *Ann. Phys., NY* **128** 188
Rozynek J 1993 *Acta Phys. Polonica* B **24** 649
Ryskin M G *et al* 1997 *Z. Phys.* C **76** 231
Saito K and Uchiyama T 1985 *Z. Phys.* A **322** 299
Saito K *et al* 1999 *Phys. Lett.* B **465** 27
Sapershtein E E and Shmatikov M K 1985 *JETP Lett.* **41** 53
Sato M *et al* 1986 *Phys. Rev.* C **33** 1062
Sawafta R *et al* 1993 *Phys. Lett.* B **307** 293
Seligman W G *et al* 1997 *Phys. Rev. Lett.* **79** 1213

Shaw G 1989 *Phys. Lett.* B **228** 125
Shlomo S and Vagradov G M 1989 *Phys. Lett.* B **232** 19
Sick I *et al* 1980 *Phys. Rev. Lett.* **45** 871
Sick I 1985 *Phys. Lett.* B **157** 13
Siegel P B *et al* 1985 *Phys. Rev.* C **31** 2184
Smirnov G I 1995 *Phys. Lett.* B **364** 87
——1999 *Eur. J. Phys.* C **10** 239
Smith J R and Miller G A 2002 *Phys. Rev.* C **65** 055206
Sokoloff M D *et al* 1986 *Phys. Rev. Lett.* **57** 3003
Soyeur M *et al* 1993 *Nucl. Phys.* A **556** 355
Sridhar K 1992 *Z. Phys.* C **55** 401
Staszel M *et al* 1984 *Phys. Rev.* D **29** 2638
Stein S *et al* 1975 *Phys. Rev.* D **12** 1884
Stewart C *et al* 1990 *Phys. Rev.* D **42** 1385
Strauch S *et al* 2002 *e-Print Archive*:nucl-ex/021022
Sukhatme U *et al* 1992 *Z. Phys.* C **53** 439
Suzuki T and Sakai H 1999 *Phys. Lett.* B **455** 25
Szwed J 1983 *Phys. Lett.* B **128** 245
Taddeucci T N *et al* 1994 *Phys. Rev. Lett.* **73** 3516
Titov A I 1984 *Sov. J. Nucl. Phys.* **40** 50
Towner I S 1986 *Comm. Nucl. Part. Phys.* **15** 145
Traini M 2001 *Nucl. Phys.* A **694** 325
Ulmer P E *et al* 1987 *Phys. Rev. Lett.* **59** 2259
van der Steenhoven G *et al* 1986 *Phys. Rev. Lett.* **57** 182
——1987 *Phys. Rev. Lett.* **58** 1727
Vary J P 1984 *Nucl. Phys.* A **418** 195c
Vasiliev M A *et al* 1999 *Phys. Rev. Lett.* **83** 2304
von Reden K F *et al* 1990 *Phys. Rev.* C **41** 1084
Wakasa T *et al* 1999 *Phys. Rev.* C **59** 3177
West G B 1975 *Phys.Rep.* **18** 263
Whitney R R *et al* 1974 *Phys. Rev.* C **9** 2230
Wilkinson D H 1973 *Nucl. Phys.* A **209** 470
Williamson C F *et al* 1997 *Phys. Rev.* C **56** 3152
Yamauchi Y and Wakamatsu M 1986 *Phys. Lett.* B **172** 161
Yamazaki T 1985 *Phys. Lett.* B **160** 227
Yang U K *et al* 2001a *Phys. Rev. Lett.* **86** 2742
——2001b *Phys. Rev. Lett.* **87** 251802
Yates T C *et al* 1993 *Phys. Lett.* B **312** 382
Yen G *et al* 1989 *Phys. Lett.* B **218** 408
——1990 *Phys. Rev.* C **42** 1665
Yoshida K and Toki H 1999 *Nucl. Phys.* A **648** 75
Zghiche A *et al* 1994 *Nucl. Phys.* A **572** 513
Zhu W and Shen J G 1989 *Phys. Lett.* B **219** 107
Zhu W *et al* 1985 *Phys. Lett.* B **154** 20
Zimmerman P *et al* 1979 *Phys. Rev.* C **19** 279
Zimmerman P 1982 *Phys. Rev.* C **26** 265
Zotov N P *et al* 1984 *JETP Lett.* **40** 965