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MEASUREMENT OF THE DEUTERON STRUCTURE FUNCTION F_2^d AND
A COMPARISON OF PROTON AND NEUTRON STRUCTURE

The European Muon Collaboration

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ABSTRACT

The deuteron structure function F_2^d has been measured in 280 GeV μ^+d interactions. Existing measurements of F_2^p , made with the same apparatus, are used to calculate $F_2^p - F_2^n$ and F_2^n/F_2^p . The ratio F_2^n/F_2^p has a similar x dependence to that of earlier measurements at lower Q^2 .

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The European Muon Collaboration has carried out a programme of measurements with a deuterium target to determine the deuteron structure function F_2^d . First results with a muon energy of 280 GeV are presented here. Using the same apparatus [1], the proton structure function F_2^p has also been reported for incident muons with energies from 120 to 280 GeV [2].

By comparing the deuteron structure function F_2^d with the proton structure function F_2^p it is possible to gain some insight into nucleon structure. In the quark-parton model the quantity F_2^n/F_2^p places experimental constraints on the u, d and diquark content of the nucleon. In addition, for field theories of the strong interaction, the flavour non-singlet structure function $F_2^p - F_2^n$ has a particularly simple evolution with Q^2 , since it does not depend upon the gluon distribution.

Assuming one-photon exchange, the differential cross-section for inelastic muon-deuteron scattering is

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

where Q^2 is the square of the 4-momentum transfer from the muon, E is the beam energy, and y is v/E where v is the energy transferred from the muon. To enable easy comparison with measurements of F_2^p , M is taken to be the proton mass, and hence the Bjorken scaling variable $x = Q^2/2Mv$ has a possible range from 0 to 2. The deuteron structure functions F_1^d and F_2^d may be related using $R = \sigma_L/\sigma_T$, the ratio of the longitudinal and transverse virtual photon-deuteron cross-sections.

$$\frac{2xF_1^d}{F_2^d} = \left(1 + \frac{4M^2x^2}{Q^2}\right) / (1 + R).$$

The structure function F_2^d , presented in this paper, has been extracted assuming $R=0$, consistent with results from muon-proton scattering already reported by the EMC [3], in the same x and Q^2 range.

The experiment was performed at the CERN SPS accelerator using 280 GeV positive muons incident on a 6m liquid deuterium target. The experimental details and the procedure for extracting F_2^d were almost identical to those of the proton structure function measurements. In calculating the radiative tails from elastic $\mu d \rightarrow \mu d$ and quasi-elastic $\mu p \rightarrow \mu p$ and $\mu n \rightarrow \mu n$, the elastic scattering was ignored and, in compensation, the quasi-elastic scattering was not suppressed at low Q^2 . This produces a good approximation to the deuteron form factor at low Q^2 [4] and was considered adequate since the radiative tail is nowhere more than 12% of the cross-section for the data presented.

The structure function $1/2 F_2^d$ is shown in Fig. 1. The errors given are statistical only; the estimated systematic errors are of similar size to those of the EMC measurements of F_2^p with the same beam energy [2]. The range in Q^2 of these data is restricted since only one beam energy has been used. Nonetheless, scaling violations are clearly visible as a rise with Q^2 at low x , and the behaviour at high x is consistent with the small scaling violations observed in F_2^p .

To obtain F_2^{p+n} and hence F_2^n from the measured F_2^d , corrections must be applied for the effects of nuclear binding. These corrections are believed to be due mainly to the Fermi motion of the nucleons, but there has been considerable debate [e.g. 5,6,7] about the most appropriate procedure for performing the calculations. Correction factors were calculated using the approaches of both Atwood and West [5] and Frankfurt and Strikman [6], assuming several different deuteron wave-functions. The corrections for $x < 0.65$ were always less than 2%, but within this limit they varied according to the wave-function and, in particular, to the method of calculation. For consistency with the SLAC-MIT deuteron data [8], the Atwood and West prescription was used but with a modified Hulthen wave-function instead of Hamada-Johnson [9]. This choice was made for computational convenience since, of the two wave-functions, the Fourier transform of the first can be done analytically. The difference leads to a less than 1% effect on the correction factor.

The structure function $F_2^p - F_2^n$, calculated as $2F_2^p - F_2^{p+n}$, is shown in fig. 2 as a function of x . The values of F_2^p used are those already

published by the EMC [2]. The measurements at different values of Q^2 , but the same x , have been averaged, the mean Q^2 increasing from 10 to 80 GeV^2 between $x = 0.03$ and 0.65. If instead of a simple average, the data are first projected to $Q^2 = 30 \text{ GeV}^2$ using a leading order QCD fit with Λ fixed at 150 MeV, the points move by much less than their statistical errors. Since $F_2^P - F_2^n$ is the difference of two measurements which approach each other at low x , the statistical and systematic errors are relatively larger than for either F_2^P or F_2^n .

A measurement of $F_2^P - F_2^n$ allows a test of a simple quark-parton model sum rule:

$$\int_0^1 \frac{dx}{x} (F_2^P - F_2^n) = \frac{1}{3} \int_0^1 dx (u_{\text{valence}} - d_{\text{valence}}) = \frac{1}{3}$$

This is strictly true only if $\bar{u} = \bar{d}$. In order to evaluate the sum rule, the data in fig. 2 were fitted with the functional form:

$$F_2^P - F_2^n = Ax^{0.5}(1-x)^\alpha(1+\beta x)$$

and the fitted curve is shown in the figure. Integration under the curve within the range of the data gives:

$$\int_{0.03}^{0.65} \frac{dx}{x} (F_2^P - F_2^n) = 0.18 \pm 0.01 \text{ statistical} \pm 0.07 \text{ systematic}$$

whereas extrapolation to $x = 0$ and $x = 1$ gives

$$\int_0^1 \frac{dx}{x} (F_2^P - F_2^n) = 0.24 \pm 0.02 \text{ statistical} \pm 0.13 \text{ systematic}$$

The observed Q^2 dependence of $F_2^P - F_2^n$ is consistent with the small scaling violations measured in the structure function F_2^P [10]. In the fits to F_2^P the dominant uncertainty in extracting the Λ parameter of QCD was the extent to which fits were affected by the poorly known gluon distribution. Fits to $F_2^P - F_2^n$ do not suffer from this defect, but the relatively large systematic and statistical uncertainties of the present data prevent any improvement on the existing determination of Λ [10].

Simultaneous studies of proton and neutron structure functions at high x give indications of the relative proportions of u and d quarks in each nucleon. The simplest quark-parton model guess is that all valence quarks

have the same x distribution, and hence for a proton $u = 2d$ and F_2^n/F_2^p tends to $2/3$ in the region where sea contributions are unimportant. However, using SU(6) spin wave-functions and arguing that high x quarks carry their parent nucleon's helicity, Farrar and Jackson [11] predict that $u = 5d$ and $F_2^n/F_2^p = 3/7$ are to be expected as x tends to 1. Assuming isospin invariance and that $d = 0$ the quark-parton model lower bound is that $F_2^n/F_2^p = 1/4$.

Fig. 3 shows the EMC measurements of F_2^n/F_2^p as a function of x . Also shown is a dotted area showing the range of the SLAC measurements of this ratio for $Q^2 > 2 \text{ GeV}^2$ and $W > 2 \text{ GeV}$, and a band indicating the magnitude of the EMC systematic uncertainties. The EMC measurements of F_2^n/F_2^p showed no significant Q^2 dependence in any x range, and so the points in fig. 3 are the average values of the ratio at each x value. It is clear that, given the errors, there is no evidence for a change in the ratio between the SLAC-MIT Q^2 range (2.5 to 20 GeV^2) and that of EMC (7 to 170 GeV^2), and that, at high x , the trend is towards values significantly below the naive QPM prediction of $2/3$. Donnachie and Landshoff [12] have pointed out that the SLAC data are not in conflict with $u = 2d$ if a very high diquark content is assumed in the x -range where F_2^n/F_2^p falls below $2/3$. However, the $1/Q^2$ fall off in diquark/single quark scattering would raise F_2^n/F_2^p to close to $2/3$ in the EMC Q^2 range, and thus, in its simple form with $u = 2d$, this diquark model is not favoured by the data.

In conclusion, measurement of F_2^d made with a 280 GeV muon beam has been presented. The integral $\int_0^1 \frac{dx}{x} (F_2^p - F_2^n)$ has a measured value consistent with the QPM prediction, but the systematic and statistical uncertainties in the data prevent the structure function $F_2^p - F_2^n$ from putting strong constraints on QCD. The ratio F_2^n/F_2^p shows no significant Q^2 dependence in comparison with lower Q^2 SLAC measurements, and thus disfavors a particular diquark model. At the highest x values of our data F_2^n/F_2^p has fallen significantly below the level of $2/3$ predicted by the naive quark-parton model.

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FIGURE CAPTIONS

Fig. 1 The deuteron structure function $1/2 F_2^d$, with statistical errors only, assuming $R = 0$.

Fig. 2 $F_2^p - F_2^n$ as a function of x , averaged over Q^2 . The points are shown with statistical errors only. The curve is a fit of the form $Ax^{0.5}(1-x)^{\alpha}(1+\beta x)$.

Fig. 3 F_2^n/F_2^p as a function of x compared with various expectations for its value at high x . The shaded band is an estimate of the systematic uncertainty as a function of x . The shaded area shows the range of the SLAC measurements.

FIG. 1

FIG. 2

FIG. 3