Analysis of scaling violation in nucleon structure functions

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Some new measurements of the nucleon structure functions F_2 and xF_3 have been carried out in an antineutrino experiment with a 15-foot bubble chamber. The structure functions are analyzed. The scaling violation in xF_3 can be described by quantum-chromodynamics effects with the scaling parameter $\Lambda_{\overline{MS}} \approx 0.3$ GeV and also by higher-twist effects.

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Scaling violation in the nucleon structure functions[1] is of interest because it presents the possibility of testing the predictions of quantum chromodynamics,[2] which is

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a candidate for the position of the correct theory of strong interactions.

In this letter we report an analysis of the nucleon structure functions obtained in an experiment on deep-inelastic scattering of neutrinos (ν_μ) and antineutrinos ($\bar{\nu}_\mu$) by an isoscalar target. The experiments were carried out in a 15-foot bubble chamber filled with a neon-hydrogen mixture (64% of the atoms were Ne atoms), which was exposed to a broad $\bar{\nu}_\mu$ beam (the ν_μ admixture was $\sim 7\%$) on the Fermilab accelerator at a primary-proton energy of 400 GeV. The statistical base consisted of 7197 $\bar{\nu}_\mu N$ and 1202 $\nu_\mu N$ inelastic interactions in the charged current which met the following criteria: The energy of the incident neutrino (or antineutrino) was $10 < E < 200$ GeV; the muon energy was $E_\mu > 4$ GeV, and the energy transfer to the hadron system was $\nu > 0.5$ GeV. The experimental conditions and the data correction methods are described in Ref. 3.

In terms of the nucleon structure functions F_i, the differential cross sections for the scattering $\overset{(-)}{\nu}_\mu N \to \mu X$ are[4]

$$\frac{d^2 \sigma^{\overset{(-)}{\nu}_\mu}}{dxdy} = \sigma_0 E \left\{ \left[1 - y - \frac{mxy}{2E} + (1 - R')\frac{y^2}{2} \right] F_2(x, Q^2) \overset{(-)}{+} \left(y - \frac{y^2}{2} \right) xF_3(x, Q^2) \right\}$$

where $\sigma_0 = G^2 m/\pi \approx 1.58 \times 10^{-38}$ cm^2/GeV, $F' = 1 - 2xF_1/F_2$, Q^2 is the negative square 4-momentum transfer to the hadron system, and $y = \nu/E$ and $x = Q^2/2m\nu$ are the standard scaling variables. The function F_2 is found from the sum of the cross sections for ν_μ and $\bar{\nu}_\mu$, and the function xF_3 is found from the difference between these cross sections. Since we found the value $R' = 0.03 \pm 0.12$ in this experiment,[3] we adopted $R' = 0$. The flux densities $\overset{(-)}{\nu}_\mu$, required for calculating the cross sections, were determined from the measured energy spectra of the $\overset{(-)}{\nu}_\mu N$ interactions under the assumption that the total cross sections in the charged current increase linearly with the energy. We used slopes for the total cross sections found by taking averages over all the data available: $\sigma^{\nu_\mu}/E = 0.64 \times 10^{-38}$ cm^2/GeV and $\sigma^{\bar{\nu}_\mu}/E = 0.30 \times 10^{-38}$ cm^2/GeV (Ref. 5).

Figure 1 shows the Q^2 dependence of F_2 and xF_3 in various x intervals (the indicated errors are statistical and do not include the common error of 7% in the absolute normalization for F_2 or 12% for xF_3). The data from the present experiments agree, within the errors, with the results reported by the CDHS group.[6] Figure 2 demonstrates the Q^2 dependence of the Nachtmann moments[4] of xF_3. In calculating these moments we took quasielastic scattering into account, using a dipole parametrization of the weak nucleon form factors.[7]

We attempted to describe the scaling violation in the nonsinglet structure function xF_3 by perturbative quantum chromodynamics, using the Altarelli-Parisi evolution equation and equations for the Nachtmann moments accurate to second order in the "running" coupling constant[2] $\alpha_S(Q^2)$. In using the Altarelli-Parisi equation we made corrections for the target mass[4] and parametrized the boundary condition at $Q_0{}^2 = 10$ GeV^2 in the form $xF_3(x, Q_0^2) = Cx^\alpha (1 - x)^\beta$, where C is fixed by the sum rule[4] $\int_0^1 F_3 dx = 3$. For the analysis with the Altarelli-Parisi equation we used data on xF_3 from the interval $0 < x < 0.7$ and data on F_2 from the interval $0.3 < x < 0.7$ at $Q^2 > 2$

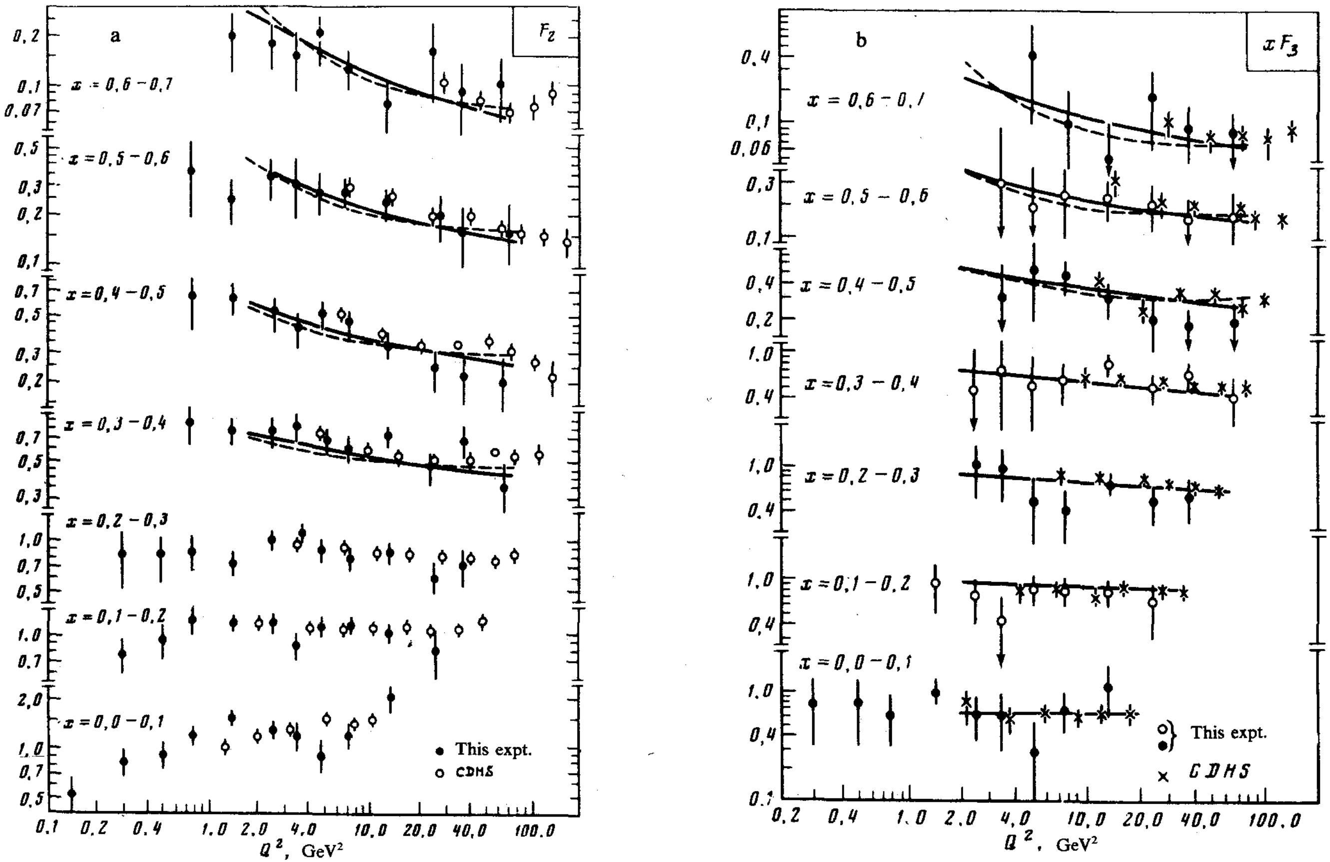

FIG. 1. The Q^2 dependence of the nucleon structure functions F_2 (*a*) and xF_3 (*b*) in various x intervals. The solid and dashed curves show the results of a fit of the Q^2 dependence of the nonsinglet structure function by quantum chromodynamics and by twist-4 effects, respectively.

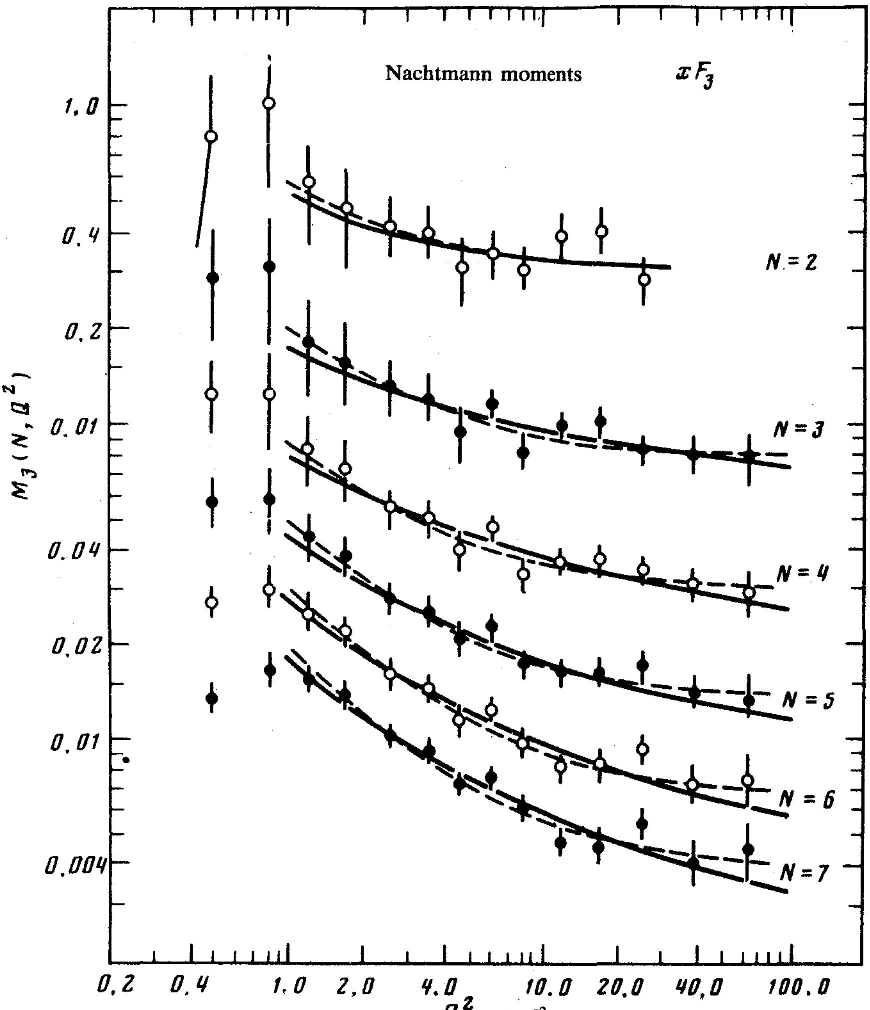

FIG. 2. The Q^2 dependence of the Nachtmann moments of xF_3. The solid and dashed curves show the results of fits of the individual moments by quantum chromodynamics and by twist-4 effects, respectively.

GeV^2. The use of the data on F_2 can be justified on the basis that the quark-sea contribution to F_2 is small at large values of x (Refs. 1 and 3). The scaling violation in the Nachtmann moments of xF_3 was analyzed at $Q^2 > 2$ GeV^2 with allowance for correlations between moments. The number of active quarks was assumed to be four.

The best description of the experimental data with the Altarelli-Parisi equation ($\chi^2/ndf = 47/77$) is found with the boundary-condition parameters $\alpha = 0.54 \pm 0.04$ and $\beta = 3.1 \pm 0.2$ and with $\Lambda_{\overline{MS}} = 0.31 \pm 0.13$ (stat.) ± 0.11 (syst.) GeV as the value of the quantum-chromodynamics scaling parameter in the $\overline{MS}$ scheme.[2] A joint analysis of the three lowest Nachtmann moments ($N = 3$, 4, 5)MH reveals $\Lambda_{\overline{MS}} = 0.28 \pm 0.07$ (stat.) ± 0.10 (syst.) GeV with $\chi^2/ndf = 20/26$. The systematic error in

$\Lambda_{\overline{MS}}$ was estimated as the linear sum of the changes in $\Lambda_{\overline{MS}}$ due to the uncertainties in the slopes of the total cross sections ($\pm 5\%$), in the normalization ($\pm 1\sigma$), and in the shape of the energy spectra of the $\overset{(-)}{\nu}_\mu N$ interactions; the nonlinear increase in the total cross sections with increasing energy due to the quantum-chromodynamics effects was also estimated.[8] The values given here for $\Lambda_{\overline{MS}}$ do not reflect the Fermi motion of the nucleons. Taking these effects into account[9] increases the value found for $\Lambda_{\overline{MS}}$ from the analysis based on the Altarelli-Parisi equation by ~ 60 MeV, while the value found for $\Lambda_{\overline{MS}}$ from the Nachtmann-moment analysis does not change. Use of the value $R' = 0.1$ reduces $\Lambda_{\overline{MS}}$ by ~ 60 MeV in the both cases. The value $\Lambda_{\overline{MS}} \approx 0.3$ GeV found in this experiment agrees with the values found for $\Lambda_{\overline{MS}}$ in some recent neutrino experiments.[1]

From the analysis of the moments we can determine the ratio of the anomalous dimensionalities d_N/d_K, which are fixed by the theory.[2] We find $d_7/d_3 = 0.25 \pm 0.25$ and $d_5/d_3 = 1.69 \pm 0.17$, in agreement with the values of 2.15 and 1.66 expected in quantum chromodynamics with corrections of second order in $\alpha_S(Q^2)$.

The violation of scaling in our data, however, can be described not only by a logarithmic Q^2 dependence, as predicted by perturbative quantum chromodynamics, but also the dependence $\propto 1/Q^{2k}$ expected for higher-twist effects.[10] The situation is illustrated in Figs. 1 and 2, which show the results of an analysis of the experimental data on the sole basis of twist-4 effects. The Q^2 dependence of xF_3 was fitted by the expression $xF_3(x,Q^2) = xF_3(x,Q_0^2)\times(1 + \mu x/(1-x)/Q^2)$, while $M_3(N,Q^2) = A_N(1 + \mu_N/Q^2)$ is used for the Nachtmann moments. The boundary condition on $xF_3(x,Q_0^2)$ was chosen as before, while μ, A_N, and μ_N were left as adjustable parameters. Because of the strong correlation between quantum chromodynamics and twist-4 effects, it was not possible to determine separately their contributions to the scaling violation.

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