Measurement of xF_3 and F_2 Structure Functions in Low Q^2 Region with the IHEP-JINR Neutrino Detector

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The isoscalar structure functions xF_3 and F_2 are measured as functions of x averaged over all Q^2 permissible for the range of 6 to 28 GeV of incident neutrino (anti-neutrino) energy at the IHEP-JINR Neutrino Detector. The QCD analysis of xF_3 structure function provides $\Lambda^{(4)}_{\overline{MS}} = (411 \pm 200)$ MeV under the assumption of QCD validity in the region of low Q^2. The corresponding value of the strong interaction constant $\alpha_S(M_Z) = 0.123^{+0.010}_{-0.013}$ agrees with the recent result of the CCFR collaboration and with the combined LEP/SLC result.

In this paper we present the measurements of the xF_3 and F_2 structure functions (SF) and the QCD analysis of xF_3 in the kinematic region of relatively small momentum transfer $0.55 < Q^2 < 4.0$ GeV^2. The analysis is based on data collected with three independent exposures of the IHEP-JINR Neutrino Detector [1] to the wide-band neutrino and anti-neutrino beams [2] of the Serpukhov U-70 accelerator. The energy of the resulting ν_μ ($\overline{\nu}_\mu$) was in the range of $6 < E_{\nu(\overline{\nu})} < 28$ GeV. The experimental set-up and the selection criteria of charged current (CC) neutrino and anti-neutrino interactions are discussed in [3]. We restricted the range of measurements to $W^2 > 1.7$ GeV^2 in order to reject quasi-elastic and resonance events and select mainly deep-inelastic ν_μ and $\overline{\nu}_\mu$ interactions. There were selected 5987 of ν_μ CC and 741 $\overline{\nu}_\mu$ CC events. The SF were measured as functions of x averaged over all Q^2 permissible for the energy range $6 < E_{\nu(\overline{\nu})} < 28$ GeV. The events were binned in intervals of x, and the values of xF_3 and F_2 were calculated in these intervals.

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The standard procedure for F_2 and xF_3 extraction was used taking the Callan-Gross relation into account. The number $n^{\nu(\overline{\nu})}$ of neutrino (anti-neutrino) interactions in a given bin of x was obtained from the measured number of neutrino (anti-neutrino) events in this bin corrected for acceptance, smearing effects arising from Fermi motion and measurement uncertainties, radiative effects (following the prescription given by De Rújula et al. [4]) and target non-isoscalarity (assuming $d_v/u_v = 0.5$) [5]. To determine appropriate correction factors, the Monte Carlo simulation of the experimental set-up has been carried out using the CATAS program [6]. We used the Buras and Gaemers parameterization for quark distributions. The charm quark content of the nucleon was assumed to be zero. The kinematic suppression of $d \to c$ and $s \to c$ transitions was taken into account assuming slow rescaling [7]. The Fermi motion of nucleons was simulated according to [8]. The details of the Monte Carlo simulation are described in [3,9].

The number of interactions in a given bin of x is subjected to kinematic constraints imposed by the cuts on the muon momentum

Table 1
The isoscalar structure functions F_2 and xF_3 obtained with the assumption of $R = 0$. The difference ΔF_2 between the values of F_2 obtained with $R = 0.1$ and with $R = 0$ is also presented. The bin edges are at x = 0.02, 0.1, 0.2, 0.3, 0.4, 0.5 and 0.65. The shown systematic errors do not include the normalization error of 4% for F_2 and 11% for xF_3 originating from the uncertainties in the ν_μ and $\overline{\nu}_\mu$ flux prediction [10].

$\langle x \rangle$	$\langle Q^2 \rangle$, GeV^2	F_2	*stat*	*syst*	ΔF_2	xF_3	*stat*	*syst*
0.052	0.55	1.169	.039	0.047	0.023	0.445	.458	0.062
0.148	1.4	1.097	.036	0.022	0.022	0.583	.087	0.017
0.248	2.2	0.894	.032	0.018	0.019	0.622	.075	0.019
0.346	2.9	0.576	.028	0.017	0.013	0.556	.109	0.011
0.447	3.4	0.390	.025	0.012	0.009	0.336	.070	0.007
0.563	4.0	0.182	.017	0.004	0.004	0.177	.117	0.005

($p_\mu > 1$ GeV/c [3]), on the neutrino (anti-neutrino) energy ($6 < E_{\nu(\overline{\nu})} < 28$ GeV) and on the invariant mass square of the hadronic system ($W^2 > 1.7$ GeV^2). These constraints were taken into account in the calculation of the flux integrals by appropriate modification of the volume of integration.

The measured values of F_2 and xF_3 structure functions are given in Table 1. The systematic errors presented in Table 1 come from the uncertainties in the knowledge of neutrino flux and cross-sections [3], imperfect detector calibration and uncertainties in the correction factors due to the choice of the input quark distributions. The overall normalization error, originating from the uncertainties in the ν_μ and $\overline{\nu}_\mu$ flux prediction [10], was estimated to be 4% for F_2 and 11% for xF_3. The correction factor uncertainties were evaluated by repeating the calculation of the SF using the Field-Feynman [11] and GRV [12] parameterizations of quark distributions.

The obtained experimental data on the xF_3 were then compared with the QCD prediction for Q^2-evolution by the Jacobi polynomials method in the next-to-leading order (NLO) QCD approximation [13,14].

The Q^2-evolution of Mellin moments

$$M_3^{QCD}(N,Q^2) \quad = \quad \int_0^1 x^{N-2} x F_3(x,Q^2)\, dx, \quad (1)$$

with N = 2,3, ..., is defined by QCD [15]:

$$M_3^{QCD}(N,Q^2) = \left[\frac{\alpha_S\left(Q_0^2\right)}{\alpha_S\left(Q^2\right)}\right]^{d_N} \frac{H_N\left(Q^2\right)}{H_N\left(Q_0^2\right)} \times M_3^{QCD}(N,Q_0^2), \quad N = 2,3,\ldots \quad (2)$$
$$d_N = \gamma_N^{(0)NS}/2\beta_0, \quad \beta_0 = 11 - 2/3 n_f.$$

Here $\alpha_s(Q^2)$ is the strong interaction constant, $\gamma_N^{(0)NS}$ are the non-singlet leading order anomalous dimensions and n_f is the number of flavors. The factor $H_N(Q^2)$ contains all higher order QCD corrections [14,16].

The unknown coefficients $M_3^{QCD}(N,Q_0^2)$ in (2) could be parameterized as the Mellin moments of some function:

$$M_3^{QCD}(N,Q_0^2) \quad = \quad \int_0^1 x^{N-2} A x^b (1-x)^c\, dx, \quad (3)$$

where the constants A, b and c should be determined from the fit to the data.

The higher-twist (HT) contribution is also taken into account: $xF_3(x,Q^2) = xF_3^{QCD}(x,Q^2) + \frac{h(x)}{Q^2}$, where $h(x) = 0.166 - 3.746\, x + 9.922\, x^2 - 6.730\, x^3$ is chosen by an interpolation of the NLO result for the HT contribution from [17].

Using nine Mellin moments and taking into account target mass corrections, we have determined three parameters – b, c and the QCD parameter $\Lambda_{\overline{MS}}$ (Table 2). We have fixed the value of parameter A using the Gross-Llewellyn Smith sum rule Q^2 - dependence: $S_{GLS} = 3\,(1 -$

Table 2
The results of the NLO QCD fit to the xF_3 SF data for $n_f = 4$, $Q_0^2 = 3$ GeV^2, $N_{max} = 9$.

χ^2	0.22
A	10.4 (fixed)
b	0.86 ± 0.14
c	3.83 ± 0.61
$\Lambda^{(4)}_{\overline{MS}}$	(411 ± 200) MeV

$\frac{\alpha_s(Q_0^2)}{\pi}$) . Three sources of errors – statistical, systematic and normalization – were summed up in quadrature. The errors for the free parameters corresponding to the 70% confidence level were obtained using the procedure described in [19].

The parameter $\Lambda^{(4)}_{\overline{MS}} = (411 \pm 200)$ MeV of the fit to the xF_3 SF data is in agreement with the NLO analyses with HT contribution of the CCFR xF_3 data: $\Lambda^{(4)}_{\overline{MS}} = (381 \pm 53\,(stat) \pm 17(HT))$ MeV [20] and $\Lambda^{(4)}_{\overline{MS}} = (428 \pm 158\,(exp))$ MeV [18].

The value of $\Lambda^{(4)}_{\overline{MS}}$ obtained from the NLO analysis of the xF_3 SF provides the value of the strong interaction constant at the point of Z boson mass of $\alpha_S(M_Z) = 0.123^{+0.010}_{-0.013}$ which is in agreement with the result of the analysis of the CCFR data $\alpha_s(M_Z) = 0.119 \pm 0.002\,(exp) \pm 0.004\,(theory)$ [20] and with the combined LEP/SLC result $\alpha_s(M_Z) = 0.124 \pm 0.0043$ [21].

We have found that the NNLO QCD fit breaks down due to the huge value 46.155 in the expression of the coefficient function of the second moment : $H_2(Q^2) = 1 - 0.132\ \alpha_s(Q^2)/4\pi - 46.155\ (\alpha_s(Q^2)/4\pi)^2 + ...$ For detailed discussion of this evidence see [18,22].

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