Proton and deuteron F_2 structure function at low Q^2

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Measurements of the proton and deuteron F_2 structure functions are presented. The data, taken at Jefferson Lab Hall C, span the four-momentum transfer range $0.06 < Q^2 < 2.8\,\mathrm{GeV}^2$ and Bjorken x values from 0.009 to 0.45, thus extending the knowledge of F_2 to low values of Q^2 at low x. Next-to-next-to-leading-order calculations using recent parton distribution functions start to deviate from the data for $Q^2 < 2\,\mathrm{GeV}^2$ at the low and high x values. Down to the lowest value of Q^2, the structure function is in good agreement with a parametrization of F_2 based on data that have been taken at much higher values of Q^2 or much lower values of x, and which are constrained by data at the photon point. The ratio of the deuteron and proton structure functions at low x remains well described by a logarithmic dependence on Q^2 at low Q^2.

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Deep inelastic scattering (DIS) remains a powerful tool for studying the partonic subtructure of the nucleon. Decades of experiments with high-energy electron and muon beams have provided a detailed map of the nucleon structure function $F_2(x, Q^2)$ over many orders of magnitude in x and Q^2 [1]. Here, Q^2 is the negative square of the four-momentum transfer of the virtual photon exchanged in the scattering process, and $x = Q^2/2M\nu$ is the Bjorken scaling variable, with M the nucleon mass and ν the energy of the virtual photon in the target rest frame. In the region of large Q^2 and ν, the results of these DIS measurements are typically interpreted in terms of partons (quarks and gluons), where x can be interpreted as the fraction of the nucleon momentum carried by the struck parton.

In this regime, a rigorous theoretical framework is provided by perturbative quantum chromodynamics, which gives logarithmic scaling violations in Q^2 [2]. However, this description starts to fail when nonperturbative effects, such as interactions between the quark struck in the scattering process and other quarks or gluons in the nucleon, become important. The sensitivity for such higher-twist effects increases with decreasing Q^2, since they are proportional to powers of $1/Q^2$. Therefore, the interpretation of the nucleon structure functions in terms of partons was originally anticipated to become suspect when momentum and energy transfers get below a few GeV. Nonetheless, the perturbative descriptions were shown to hold down to surprisingly low values of Q^2, of the order of $1\,\mathrm{GeV}^2$, provided that the energy transfer remained sufficiently large [3].

For small values of the energy transfer, corresponding to an invariant mass $W = \sqrt{M^2 + 2M\nu - Q^2} < 2\,\mathrm{GeV}$ of the hadronic system, the data at low Q^2 prominently show excitation of nucleon resonances, and a simple partonic interpretation fails. As we move beyond this resonance region, the behavior of the nucleon structure functions in the low-Q^2 region is thought to shed light on the transition from perturbative to nonperturbative QCD within the partonic interpretation. However, little is known about this behavior, since for $W > 2\,\mathrm{GeV}$ there are few data points at low Q^2, except for the (transverse) cross section σ_T at exactly $Q^2 = 0$ from real-photon absorption experiments, some data from the SLAC [4], and data at very low x values ($x < 0.005$) from the E665, ZEUS, and H1 experiments [5–7]. Here, we report on measurements in the range $0.009 < x < 0.45$, approaching the valence-quark region, for $0.06 < Q^2 < 2.8\,\mathrm{GeV}^2$.

The differential cross section for inclusive electron scattering can be written as

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma_v(\sigma_T + \varepsilon\sigma_L), \tag{1}$$

where ε is the virtual photon polarization,

$$\varepsilon = \left(1 + \frac{2|\mathbf{q}|^2}{Q^2}\tan^2\frac{\theta_e}{2}\right)^{-1}, \quad (2)$$

σ_L (σ_T) is the longitudinal (transverse) virtual-photon absorption cross section, which depends on x and Q^2, and the virtual-photon flux factor is given by

$$\Gamma_v = \frac{\alpha}{2\pi^2}\frac{E'}{E}\frac{K}{Q^2}\frac{1}{1-\varepsilon}, \quad (3)$$

with $K = (W^2 - M^2)/2M$. Usually, the cross section is written in terms of the structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$, where F_1 is proportional to σ_T and F_2 is proportional to $\sigma_L + \sigma_T$. However, the cross section can also be written in terms of F_2 and the ratio $R \equiv \sigma_L/\sigma_T$ according to

$$\frac{d^2\sigma}{d\Omega\, dE'} = \frac{4\pi^2\alpha}{1-x}\frac{1}{Q^2}\left(1 + \frac{4M^2x^2}{Q^2}\right)F_2\frac{1+\varepsilon R}{1+R}. \quad (4)$$

This equation shows that, in the limit $\varepsilon \to 1$, the structure function F_2 can directly be determined from the measured cross section. Otherwise, measurements have to be performed for at least two different values of ε (beam energies) at fixed values of x and Q^2 (Rosenbluth separation), or a value for R has to be assumed. Although results for the F_2 structure function have been widely reported [4–19], in many cases assumptions on the value of R were made. A more limited set of experiments actually performed Rosenbluth separations [4,8,10–14]. In this paper, we present results for F_2 based on data for both hydrogen and deuterium at low values of Q^2, utilizing both techniques: using Rosenbluth-separated data and using unseparated data in combination with a parametrization of $R(x, Q^2)$. Values of R extracted from these data for those kinematics where data were taken at more than one value of ε, were reported previously [20]. Here the full data set is used to determine F_2.

The experiment (E99-118) was carried out in experimental Hall C at the Thomas Jefferson National Accelerator Facility (JLab). Data were obtained for $0.009 < x < 0.45$, $0.06 < Q^2 < 2.8\,\mathrm{GeV}^2$ by utilizing 2.301-, 3.419-, and 5.648-GeV electron beams at a current of $I = 25\ \mu$A. The minimum scattered electron energy was $E' \approx 0.4\,\mathrm{GeV}$, and the range of the invariant mass of the hadronic system W was between 1.9 and $3.2\,\mathrm{GeV}^2$. Electrons scattered from 4-cm-long liquid hydrogen and deuterium targets were detected in the high-momentum spectrometer (HMS) in Hall C at various angles between 10° and 60°.

The inclusive double-differential cross section for each energy and angle bin within the spectrometer acceptance was determined from the measured electron yields. The yields were corrected for detector inefficiencies, background events, and finally radiative effects to obtain the Born cross section. Internal bremsstrahlung, vertex corrections, and loop diagrams were calculated using the approach of Akhundov *et al.* [21]. The code used includes the possibility that the electron emits two hard photons (α^2 term). However, the calculation of this process is not yet fully established. Because the calculation including the α^2 term overestimates the radiative tail, perhaps because higher-order terms associated with the emission of more than two hard photons are not negligible, only half of the two-hard-photon correction was applied, and the size of the correction was included in the cross-section systematic uncertainty (see Ref. [22] for more details). Additional radiative effects in the target and its exit windows were determined using the formalism of Mo and Tsai [23].

For every bin, the cross section was corrected for the variation of the cross section over the acceptance with the angle θ to yield the value of the cross section at the central angle (bin-centering correction). To minimize the dependence on the model used to describe this variation and the radiative effects, an iterative procedure was employed. A similar procedure was used to center the cross sections at chosen values of x. For details regarding the analysis and the standard Hall C apparatus employed in this experiment, see Refs. [20,22,24,25].

The total uncertainty in the cross sections was calculated as the quadratic sum of statistical and systematic uncertainties. The statistical uncertainty was in most cases well below 1%. The systematic uncertainty on the cross sections from instrumental sources such as target thickness, charge integration, various efficiencies, and acceptance amounted to 1.3%–1.7%. The uncertainty in the radiative corrections is about 1%, except at low values of E' ($E' < 0.8\,\mathrm{GeV}$), where the measured data are dominated by events from elastic or quasielastic scattering with the emission of one or more photons in the initial or final state. The estimate of these uncertainties was determined by varying all relevant input cross sections within their uncertainties, and amounted to 1.5% for hydrogen and 8.5% for deuterium in the most extreme cases considered. The much larger uncertainty in the deuterium cross section is because of the contribution from quasielastic scattering, which can only be modeled approximately due to the lack of low-Q^2 ($<0.4\,\mathrm{GeV}^2$) electron-deuteron scattering data over a sufficiently wide range of energy transfers. In addition, there is the uncertainty from the α^2 term, which can be as large as 50% in a few cases (low values of x and ε).

The results for the $F_2(x, Q^2)$ structure function for protons (deuterons) from the Rosenbluth-separated data are shown as the open squares in Figs. 1 and 2 as a function of Q^2 for fixed values of x. The value of F_2 and its uncertainty are in essence the result of an extrapolation of the cross sections and their (total) uncertainties, measured at the different ε values, to $\varepsilon = 1$, and were calculated accordingly. The numerical values [26] are given in Table I.

Values of F_2 from the unseparated data were determined by inversion of Eq. (4) and use of a recent parametrization of R. Measurements of $R(x, Q^2)$ from the present experiment reported in [20] showed a nearly constant behavior of R down to Q^2 of about $0.1\,\mathrm{GeV}^2$ at low values of x. This was contrary to expectations that R would decrease strongly at such low Q^2. The unexpected behavior was taken into account by extending the parametrization of Ref. [4] to $Q^2 = 0$, resulting in a new $R_{e99118}(x, Q^2)$ parametrization [20]. This parametrization was used to calculate F_2 for all values of x and Q^2 where cross sections from the present experiment are available that were not used already for the Rosenbluth separation. The uncertainty in F_2 is a combination of the uncertainties in the measured cross section and in the parametrization of R. For $Q^2 > 1\,\mathrm{GeV}^2$, the latter uncertainty was taken to be

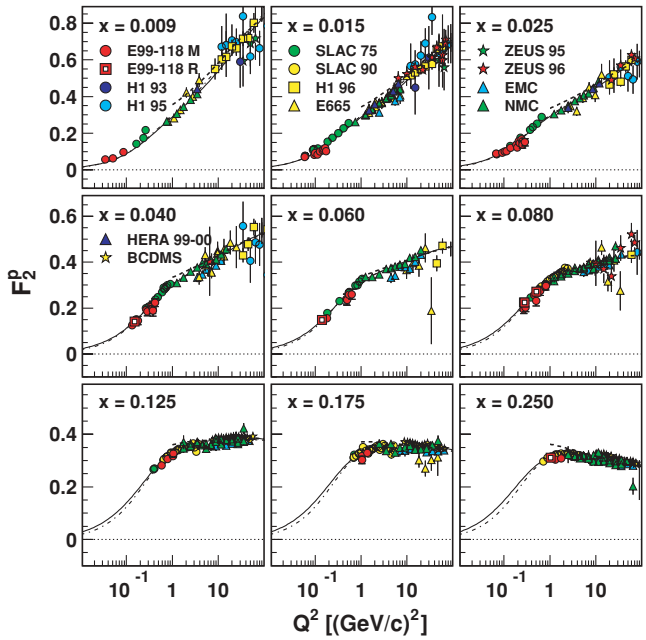

FIG. 1. (Color) Comparison of the results for $F_2^p(x, Q^2)$ from the present experiment (E99-118) to the results of other experiments. Both the Rosenbluth-separated data (open red squares) and the model-dependent extracted data (red circles) are shown. The thick dashed curve represents the result of a NNLO calculation based upon the MRST [29] parton distributions including target-mass effects. The solid and dot-dashed curves are the results of the phenomenological paramterization from Refs. [31] and [32], respectively.

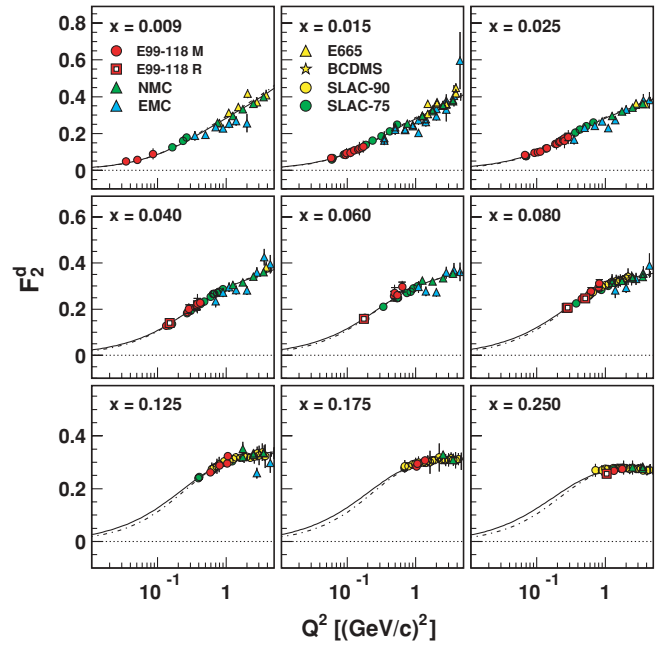

FIG. 2. (Color) Comparison of the results for $F_2^d(x, Q^2)$ from the present experiment (E99-118) to the results of other experiments. Both the Rosenbluth-separated data (open red squares) and the model-dependent extracted data (red circles) are shown. The solid and dot-dashed curves result from multiplying the phenomenological parametrizations shown in Fig. 1 with $(1 + F_2^n/F_2^p)/2$ using the NMC parametrization [27] for the ratio F_2^n/F_2^p.

0.075. For $Q^2 < 1\,\mathrm{GeV}^2$, the value of R is less well known, as there are few measurements in that region, especially at very small values of Q^2. Therefore, in this region an uncertainty increasing from 0.075 at $Q^2 = 1\,\mathrm{GeV}^2$ to 0.20 at $Q^2 = 0\,\mathrm{GeV}^2$ was taken. This gives a range for R that covers well the existing data in this region. The influence of R on the extracted value of F_2 diminishes when $\varepsilon \to 1$. The results are shown as the red circles in Figs. 1 and 2. They agree well with the Rosenbluth-separated results, but cover a much larger kinematic range. Also, there is a very good consistency between the results at the same value of x and almost the same value of Q^2, but different values of ε, as can be seen from the numerical values given in Table II. Both figures also show the results of previous measurements at SLAC [4], by the EMC [13], NMC [14,27,28], and BCDMS [8,9] collaborations at CERN, the E665 [5] collaboration at Fermilab, and the H1 [15–17] and ZEUS [18,19] collaborations at DESY. In the region of Q^2 where these overlap with the present results there is good agreement. At low x our data clearly extend the knowledge of F_2 down to much lower Q^2.

The thick dashed curves shown in Fig. 1 are the result of a next-to-next-to-leading-order (NNLO) calculation based on the recent MRST [29] parton distributions, where target-mass effects have been included according to [30]. The calculations do not extend below $Q^2 = 1\,\mathrm{GeV}^2$, as there a DIS approach is no longer assumed to be applicable. The calculated results closely coincide with the data for $x \approx 0.1$. Deviations can be noticed at the lower-Q^2 end for the lowest ($x = 0.009$) and highest ($x = 0.250$) x values. This could be due to uncertainties in the used parton distribution functions at low x and the influence of higher-twist effects.

The solid and dot-dashed curves shown in Fig. 1 represent two existing parametrizations down to the photon point of the world's F_2^p data, termed ALLM97 and GD07. The ALLM97 parametrization [31] represents a 23-parameter fit to the world's electron-proton scattering cross-section data, based upon a Regge-motivated approach. It includes both Reggeon and Pomeron exchange mechanisms. Deep inelastic scattering data covering a wide range in x and Q^2 are used, with additional constraints built in to connect smoothly to the

TABLE I. Data for the proton and deuteron F_2 structure function as determined via the Rosenbluth-separation method. Uncertainties are shown without (Δ_{norc}) and with (Δ_{full}) the contribution from radiative corrections.

x	Q^2	F_2^p	Δ^p_{norc}	Δ^p_{full}	F_2^d	Δ^d_{norc}	Δ^d_{full}
0.040	0.150	0.1407	0.0035	0.0046	0.1405	0.0036	0.0046
0.060	0.145	0.1477	0.0033	0.0053	0.1579	0.0034	0.0042
0.080	0.273	0.2238	0.0039	0.0053	0.2045	0.0039	0.0044
0.080	0.283	0.2250	0.0041	0.0054	0.2068	0.0038	0.0043
0.080	0.508	0.2715	0.0046	0.0074	0.2470	0.0042	0.0058
0.175	0.476	0.2753	0.0060	0.0062	0.2438	0.0119	0.0121
0.250	1.045	0.3103	0.0054	0.0057	0.2565	0.0042	0.0045
0.350	1.300	0.2674	0.0035	0.0036	0.2274	0.0051	0.0052
0.350	1.670	0.2648	0.0046	0.0046	0.2140	0.0033	0.0038

TABLE II. Data for the proton and deuteron cross sections and F_2 structure functions as determined via the model-dependent method. The cross sections do not include the virtual-photon flux factor Γ_v [see Eqs. (1) and (3)]. Uncertainties are shown without (Δ_{norc}) and with (Δ_{full}) the contribution from radiative corrections.

x	Q^2	ε	σ^p	Δ^p_{norc}	Δ^p_{full}	F_2^p	Δ^p_{norc}	Δ^p_{full}	σ^d	Δ^d_{norc}	Δ^d_{full}	F_2^d	Δ^d_{norc}	Δ^d_{full}
0.009	0.034	0.364	1.0493	0.0689	0.2085	0.0560	0.0072	0.0127	0.9381	0.0411	0.1287	0.0492	0.0060	0.0088
0.009	0.051	0.250	0.4638	0.0409	0.1754	0.0616	0.0094	0.0245	0.4489	0.0240	0.1121	0.0580	0.0082	0.0164
0.009	0.086	0.157	0.2382	0.0242	0.1282	0.0997	0.0166	0.0553	0.2233	0.0138	0.0694	0.0896	0.0137	0.0305
0.015	0.059	0.361	0.4304	0.0241	0.0692	0.0696	0.0082	0.0133	0.4232	0.0155	0.0456	0.0669	0.0077	0.0102
0.015	0.095	0.345	0.2711	0.0144	0.0421	0.0842	0.0093	0.0154	0.2754	0.0096	0.0301	0.0831	0.0091	0.0125
0.015	0.098	0.178	0.2034	0.0190	0.0990	0.0961	0.0150	0.0483	0.2056	0.0111	0.0549	0.0935	0.0133	0.0278
0.015	0.112	0.202	0.1650	0.0144	0.0712	0.0876	0.0128	0.0392	0.1893	0.0090	0.0417	0.0966	0.0130	0.0245
0.015	0.127	0.229	0.1780	0.0123	0.0514	0.1058	0.0137	0.0327	0.1878	0.0077	0.0318	0.1073	0.0134	0.0221
0.015	0.144	0.259	0.1685	0.0099	0.0372	0.1114	0.0131	0.0271	0.1773	0.0066	0.0244	0.1129	0.0131	0.0199
0.015	0.151	0.144	0.0828	0.0079	0.0421	0.1216	0.0186	0.0635	0.0846	0.0047	0.0239	0.1186	0.0166	0.0368
0.015	0.164	0.293	0.1713	0.0085	0.0270	0.1253	0.0133	0.0230	0.1742	0.0058	0.0196	0.1227	0.0131	0.0186
0.015	0.172	0.163	0.0677	0.0062	0.0305	0.1118	0.0163	0.0519	0.0816	0.0039	0.0182	0.1286	0.0169	0.0327
0.025	0.067	0.537	0.8077	0.0278	0.0482	0.0883	0.0070	0.0082	0.7744	0.0198	0.0474	0.0834	0.0066	0.0081
0.025	0.092	0.357	0.2380	0.0106	0.0280	0.0960	0.0101	0.0145	0.2422	0.0074	0.0203	0.0953	0.0101	0.0126
0.025	0.104	0.485	0.4752	0.0164	0.0327	0.1040	0.0084	0.0104	0.4636	0.0120	0.0304	0.0994	0.0082	0.0101
0.025	0.113	0.247	0.1551	0.0090	0.0360	0.1069	0.0133	0.0275	0.1534	0.0058	0.0220	0.1024	0.0125	0.0189
0.025	0.140	0.483	0.3115	0.0099	0.0173	0.1251	0.0094	0.0110	0.3075	0.0075	0.0171	0.1208	0.0093	0.0111
0.025	0.186	0.331	0.1828	0.0072	0.0207	0.1469	0.0138	0.0208	0.1849	0.0052	0.0171	0.1441	0.0138	0.0187
0.025	0.195	0.185	0.0708	0.0048	0.0234	0.1312	0.0166	0.0456	0.0807	0.0032	0.0145	0.1439	0.0173	0.0307
0.025	0.212	0.372	0.1914	0.0066	0.0151	0.1675	0.0141	0.0185	0.1816	0.0047	0.0130	0.1545	0.0134	0.0169
0.025	0.222	0.210	0.0769	0.0042	0.0168	0.1593	0.0181	0.0383	0.0786	0.0028	0.0114	0.1568	0.0176	0.0281
0.025	0.240	0.418	0.1885	0.0058	0.0111	0.1780	0.0133	0.0160	0.1801	0.0044	0.0106	0.1656	0.0128	0.0156
0.025	0.252	0.237	0.0737	0.0034	0.0120	0.1696	0.0175	0.0319	0.0786	0.0024	0.0089	0.1745	0.0181	0.0262
0.025	0.253	0.147	0.0375	0.0028	0.0144	0.1530	0.0198	0.0609	0.0410	0.0018	0.0093	0.1601	0.0193	0.0405
0.025	0.287	0.167	0.0365	0.0023	0.0103	0.1669	0.0197	0.0499	0.0413	0.0016	0.0075	0.1814	0.0204	0.0382
0.040	0.133	0.352	0.1524	0.0055	0.0134	0.1295	0.0125	0.0162	0.1546	0.0041	0.0109	0.1280	0.0126	0.0152
0.040	0.273	0.469	0.2027	0.0053	0.0088	0.2038	0.0133	0.0150	0.1905	0.0041	0.0085	0.1876	0.0126	0.0146
0.040	0.287	0.269	0.0798	0.0031	0.0093	0.2027	0.0190	0.0293	0.0812	0.0022	0.0073	0.2002	0.0190	0.0255
0.040	0.353	0.581	0.2048	0.0046	0.0057	0.2244	0.0107	0.0113	0.1926	0.0038	0.0055	0.2077	0.0103	0.0111
0.040	0.370	0.342	0.0753	0.0022	0.0047	0.2288	0.0173	0.0215	0.0723	0.0018	0.0042	0.2139	0.0166	0.0202
0.040	0.371	0.214	0.0386	0.0016	0.0055	0.2186	0.0209	0.0364	0.0393	0.0012	0.0042	0.2155	0.0206	0.0304
0.040	0.380	0.148	0.0232	0.0013	0.0061	0.2102	0.0230	0.0588	0.0255	0.0009	0.0041	0.2231	0.0235	0.0422
0.040	0.421	0.385	0.0737	0.0020	0.0036	0.2416	0.0162	0.0188	0.0708	0.0016	0.0031	0.2268	0.0157	0.0178
0.060	0.180	0.346	0.1036	0.0032	0.0070	0.1641	0.0148	0.0178	0.1045	0.0025	0.0062	0.1616	0.0149	0.0173
0.060	0.479	0.273	0.0383	0.002	0.0030	0.2622	0.0203	0.0276	0.0384	0.0009	0.0025	0.2563	0.0202	0.0253
0.060	0.491	0.190	0.0233	0.0009	0.0033	0.2617	0.0234	0.0428	0.0247	0.0007	0.0025	0.2702	0.0240	0.0355
0.060	0.543	0.483	0.0743	0.0017	0.0022	0.2751	0.0138	0.0147	0.0717	0.0014	0.0021	0.2609	0.0135	0.0145
0.060	0.633	0.243	0.0209	0.0006	0.0016	0.2863	0.0205	0.0288	0.0222	0.0005	0.0013	0.2958	0.0212	0.0263
0.080	0.456	0.704	0.2404	0.0044	0.0048	0.2650	0.0086	0.0089	0.2245	0.0038	0.0048	0.2451	0.0081	0.0086
0.080	0.617	0.538	0.0762	0.0015	0.0018	0.2935	0.0124	0.0129	0.0725	0.0013	0.0018	0.2752	0.0119	0.0127
0.080	0.619	0.348	0.0366	0.0009	0.0016	0.2960	0.0179	0.0207	0.0349	0.0008	0.0014	0.2767	0.0170	0.0194
0.080	0.799	0.438	0.0337	0.0007	0.0008	0.3128	0.0135	0.0144	0.0324	0.0006	0.0009	0.2950	0.0131	0.0143
0.080	0.818	0.310	0.0198	0.0005	0.0008	0.3227	0.0171	0.0203	0.0195	0.0004	0.0007	0.3122	0.0167	0.0195
0.125	0.588	0.825	0.2925	0.0047	0.0050	0.2876	0.0061	0.0063	0.2666	0.0041	0.0048	0.2609	0.0055	0.0061
0.125	0.797	0.657	0.0801	0.0014	0.0015	0.3179	0.0089	0.0091	0.0732	0.0012	0.0015	0.2873	0.0082	0.0090
0.125	1.032	0.544	0.0329	0.0006	0.0007	0.3319	0.0097	0.0100	0.0296	0.0005	0.0007	0.2952	0.0087	0.0097
0.125	1.056	0.391	0.0185	0.0004	0.0005	0.3491	0.0131	0.0141	0.0174	0.0003	0.0005	0.3228	0.0122	0.0144
0.175	1.029	0.778	0.0876	0.0013	0.0013	0.3242	0.0060	0.0061	0.0773	0.0011	0.0011	0.2846	0.0052	0.0053
0.175	1.045	0.294	0.0085	0.0002	0.0003	0.3235	0.0142	0.0150	0.0078	0.0002	0.0002	0.2939	0.0129	0.0141
0.175	1.365	0.488	0.0165	0.0003	0.0003	0.3447	0.0109	0.0111	0.0148	0.0003	0.0003	0.3072	0.0099	0.0107
0.250	1.332	0.661	0.0305	0.0005	0.0005	0.3126	0.0074	0.0075	0.0262	0.0004	0.0005	0.2673	0.0065	0.0065
0.250	1.761	0.599	0.0144	0.0002	0.0002	0.3183	0.0082	0.0083	0.0125	0.0002	0.0002	0.2744	0.0071	0.0071
0.450	2.275	0.715	0.0099	0.0002	0.0002	0.2104	0.0046	0.0046	0.0077	0.0001	0.0001	0.1638	0.0036	0.0036

TABLE III. Ratio of deuteron-to-proton cross sections and structure functions. Uncertainties are shown without ($\Delta_{no\alpha 2}$) and with (Δ_{full}) the contribution from radiative corrections of order α^2.

x	Q^2	ε	σ^d/σ^p	$\Delta_{no\alpha 2}$	Δ_{full}	F_2^d/F_2^p	$\Delta_{no\alpha 2}$	Δ_{full}
0.0080	0.0332	0.3521	0.8952	0.0540	0.0758	0.8798	0.0562	0.0774
0.0080	0.0509	0.2500	0.9426	0.0682	0.1339	0.9170	0.0728	0.1363
0.0080	0.0883	0.1605	0.8812	0.0719	0.1587	0.8448	0.0806	0.1628
0.0125	0.0359	0.3791	0.8513	0.0495	0.0633	0.8367	0.0516	0.0649
0.0125	0.1092	0.1977	1.0555	0.0644	0.1558	1.0129	0.0773	0.1616
0.0175	0.0593	0.3692	0.9613	0.0358	0.0418	0.9413	0.0410	0.0464
0.0175	0.0977	0.3247	1.0040	0.0373	0.0499	0.9766	0.0463	0.0569
0.0175	0.1553	0.2186	1.0137	0.0365	0.0598	0.9768	0.0519	0.0703
0.0250	0.0677	0.5390	0.9600	0.0298	0.0330	0.9452	0.0333	0.0361
0.0250	0.1085	0.3985	0.9840	0.0258	0.0282	0.9621	0.0338	0.0357
0.0250	0.2285	0.2567	0.9832	0.0247	0.0272	0.9529	0.0389	0.0405
0.0350	0.1022	0.5321	0.9646	0.0260	0.0274	0.9484	0.0306	0.0318
0.0350	0.1362	0.4030	0.9909	0.0254	0.0276	0.9689	0.0335	0.0352
0.0350	0.1765	0.2981	0.9942	0.0302	0.0408	0.9656	0.0416	0.0498
0.0350	0.3099	0.2974	0.9612	0.0221	0.0232	0.9375	0.0322	0.0329
0.0500	0.1713	0.5122	0.9732	0.0210	0.0210	0.9593	0.0251	0.0252
0.0500	0.3712	0.4090	0.9445	0.0199	0.0200	0.9273	0.0262	0.0262
0.0500	0.4644	0.2699	0.9897	0.0222	0.0232	0.9651	0.0330	0.0337
0.0700	0.2195	0.5146	0.9299	0.0213	0.0216	0.9140	0.0266	0.0268
0.0700	0.2692	0.4810	0.9576	0.0198	0.0199	0.9426	0.0247	0.0247
0.0700	0.4464	0.6947	0.9341	0.0193	0.0193	0.9253	0.0212	0.0212
0.0700	0.5624	0.4355	0.9641	0.0208	0.0210	0.9474	0.0267	0.0268
0.0700	0.6390	0.2965	0.9894	0.0225	0.0234	0.9670	0.0316	0.0323
0.0900	0.2936	0.4363	0.9530	0.0197	0.0197	0.9361	0.0259	0.0259
0.0900	0.4998	0.4794	0.9419	0.0187	0.0187	0.9310	0.0215	0.0215
0.0900	0.6328	0.5494	0.9384	0.0200	0.0200	0.9256	0.0238	0.0238
0.0900	0.7947	0.3526	0.9627	0.0212	0.0214	0.9436	0.0285	0.0286
0.1100	0.5649	0.8075	0.9197	0.0183	0.0183	0.9147	0.0190	0.0190
0.1100	0.8072	0.5470	0.9274	0.0187	0.0187	0.9162	0.0217	0.0217
0.1100	1.0138	0.4026	0.9491	0.0211	0.0211	0.9324	0.0269	0.0269
0.1400	0.4647	0.6166	0.9187	0.0182	0.0182	0.9099	0.0202	0.0202
0.1400	0.6204	0.8495	0.9080	0.0187	0.0187	0.9045	0.0190	0.0190
0.1400	0.8409	0.6831	0.9045	0.0191	0.0191	0.8967	0.0206	0.0206
0.1400	1.0623	0.5063	0.8971	0.0181	0.0181	0.8850	0.0218	0.0218
0.1800	0.5036	0.6698	0.9202	0.0183	0.0183	0.9136	0.0194	0.0194
0.1800	0.7065	0.9009	0.8918	0.0189	0.0189	0.8901	0.0190	0.0190
0.1800	0.9981	0.5371	0.8861	0.0176	0.0176	0.8802	0.0185	0.0185
0.1800	1.3393	0.5233	0.8947	0.0179	0.0179	0.8853	0.0202	0.0202
0.2250	0.7407	0.9170	0.8775	0.0173	0.0173	0.8765	0.0173	0.0173
0.2250	1.0817	0.5354	0.8625	0.0171	0.0171	0.8583	0.0176	0.0176
0.2250	1.3655	0.6727	0.8743	0.0177	0.0177	0.8700	0.0182	0.0182
0.2250	1.6733	0.5761	0.8817	0.0180	0.0180	0.8775	0.0185	0.0185
0.2750	0.7749	0.9313	0.8371	0.0176	0.0176	0.8367	0.0176	0.0176
0.2750	1.2362	0.8579	0.8305	0.0171	0.0171	0.8303	0.0171	0.0171
0.2750	1.7101	0.5221	0.8667	0.0169	0.0169	0.8653	0.0170	0.0170
0.3500	1.3006	0.5544	0.8340	0.0153	0.0153	0.8340	0.0153	0.0153
0.3500	1.7109	0.5575	0.8279	0.0153	0.0153	0.8279	0.0153	0.0153
0.3500	2.1840	0.6967	0.8243	0.0167	0.0167	0.8243	0.0167	0.0167
0.4500	2.3660	0.7325	0.7881	0.0144	0.0144	0.7881	0.0144	0.0144

photon point. The GD07 parametrization [32] includes recent data and converts from cross sections to F_2 structure functions by use of the parametrization of R from Ref. [33] for all data.

The solid (dot-dashed) curves shown in Fig. 2 were constructed by utilizing the mentioned ALLM97 and GD07 parametrizations of F_2^p and multiplying them by the factor $(1 + F_2^n/F_2^p)/2$ using a global fit to F_2^n/F_2^p data by the NMC collaboration [27]. As can be seen from Figs. 1 and 2, the existing parametrizations are in very good agreement with the measured structure functions, with deviations often below 3%

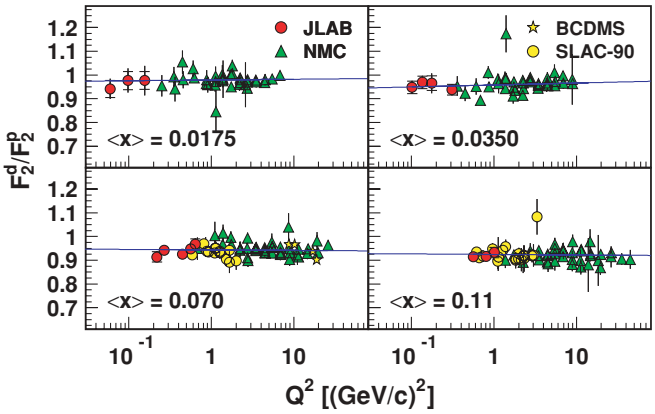

FIG. 3. (Color) Q^2 dependence of the ratio F_2^d/F_2^p for some selected x bins. Both the present data and data from previous experiments are shown. The lines are the results of a linear (in ln Q^2) fit of all data described in the text.

and always consistent given the error bars. The largest deviations occur for data that have large systematic uncertainties. Given that for $x < 0.1$ there were no data for $Q^2 \lesssim 1\,\mathrm{GeV}^2$, the agreement between our data and the parametrizations is remarkable. This indicates that the constraints imposed on the parametrizations by low-Q^2 data at much smaller x and the way the transition to the real photon point at $Q^2 = 0$ is parametrized seem to be sufficient to correctly predict $F_2(x, Q^2)$ in a region where it was hitherto unknown.

The ratio of the deuteron-to-proton structure functions, F_2^d/F_2^p, is of interest because it embodies information about the neutron structure function F_2^n. This ratio can be expressed in terms of the cross section ratio σ^d/σ^p as

$$\frac{F_2^d}{F_2^p} = \left(\frac{\sigma^d}{\sigma^p}\right)\frac{(1+\varepsilon R^p)(1+R^d)}{(1+R^p)(1+\varepsilon R^d)}\,, \tag{5}$$

with σ^d/σ^p the measured cross-section ratio and R^d and R^p both functions of x and Q^2.

For sufficiently high-energy experiments, $\varepsilon \to 1$, and the deuteron-to-proton cross section and F_2 ratios will equate. Similarly, the ratios equate if $R^p = R^d$, which has been found in all previous higher-Q^2 data, albeit with relatively large uncertainties (see Refs. [11,27]). However, the data from the present experiment are at $\varepsilon \neq 1$ and, as reported earlier [20], there may be a small reduction of R^d with respect to R^p at low Q^2 ($Q^2 < 1.5\,\mathrm{GeV}^2$). Such a reduction was taken into account when we converted our measured σ^d/σ^p ratios to F_2^d/F_2^p ratios. (The systematic error in the latter ratio includes the effect of an uncertainty in the value of $R_d - R_p$, which conservatively was taken equal to the value of $R_d - R_p$.) The effect is small, decreasing the extracted ratio F_2^d/F_2^p by up to a few percent as compared to the σ^d/σ^p ratio, depending on the value of ε and Q^2. Figure 3 shows the present F_2^d/F_2^p data for selected x bins in comparison with the world's data. The numerical values of all present data are given in Table III.

The precise data from the NMC collaboration [27] have shown that the F_2^d/F_2^p ratio depends (at fixed x) logarithmically on the scale, Q^2. The data from the present experiment extend the Q^2 range of the data in the region $0.01 < x < 0.1$, thus improving the knowledge of these logarithmic Q^2 dependences in that region. If differences in higher-twist effects in the proton and deuteron are neglected, all data for F_2^d/F_2^p were fitted with the linear function $(F_2^d/F_2^p)(x, Q^2) = A(x) + B(x)\ln(Q^2)$. The data for F_2^d/F_2^p from the present experiment are found to be in excellent agreement with this parametrization (see the lines in Fig. 3).

In summary, we present F_2 structure function data taken on hydrogen and deuterium spanning the four-momentum transfer range $0.06 < Q^2 < 2.8\,\mathrm{GeV}^2$. The data are at lower Q^2 values than hitherto reported in the range of small to intermediate x, $0.009 < x < 0.45$. The data agree well with the results of phenomenological parametrizations based upon data accumulated at either much larger Q^2 or far smaller values of x. Results of NNLO calculations agree with the data for $x \approx 0.1$, but deviate at lower and higher values of x, when Q^2 drops below $2\,\mathrm{GeV}^2$. The present data extend the data set for the ratio of deuteron-to-proton F_2 structure functions to lower Q^2. The new data are in excellent agreement with higher-Q^2 data, when the logarithmic dependence on Q^2 is taken into account.

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