Evidence for Valence Quark-Hadron Duality.

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(April 5, 1999)

A newly obtained data sample of inclusive electron-nucleon scattering from both hydrogen and deuterium targets is analyzed. These JLab data are in the nucleon resonance region in the four-momentum transfer range between 0.3 and 5 (GeV/c)^2. The data are in agreement with SLAC data at similar kinematics, and are found to follow an average scaling curve. The inclusion of low-momentum transfer data yields a scaling curve resembling deep inelastic neutrino-nucleus scattering data, suggesting a sensitivity to the valence quarks only.

Nearly thirty years ago Bloom and Gilman observed that the electroproduction of resonances resembles the scaling behavior of the deep inelastic structure function, if expressed in terms of a scaling variable connecting the two different kinematic regions, and if averaged over a large range of invariant mass W [1,2]. It was suggested that this relationship between resonance electroproduction and the scaling behavior observed in deep inelastic scattering hinted at a common origin for both phenomena, called local duality. A quantitative Quantum Chromodynamics (QCD) analysis of this empirical observation was given by De Rujula, Georgi, and Politzer [3,4]. They showed that the resonances oscillate around an average scaling curve. Although electroproduction of resonances is a strongly non-perturbative phenomenenon, the resonance strengths average to a global scaling curve, resembling the deep inelastic scaling curve, as the higher-twist effects are not large, if averaged over a large kinematic region.

The higher-twist effects can be viewed as processes where the struck quark communicates with one or more of the spectator quarks by gluon exchange. In the deep inelastic F_2 data, higher-twist terms have been found to be small for Bjorken $x < 0.40$ [5], and insignificant for $x \approx 0.01$, even at $Q^2 \simeq 1$ (GeV/c)^2, where Q is the four-momentum transfer [6,7]. On the other hand, gauge invariance requires F_2 to vanish linearly with Q^2 at $Q^2 = 0$ (GeV/c)^2 [8], suggesting non-perturbative effects to govern this region. In this Letter we assume higher-twist effects, if averaged over the full resonance region, to be small, even at relatively low momentum transfers, and thus local duality to remain valid. A quantitative verification of this assumption will be presented elsewhere [9].

A sample of high-precision data in the nucleon resonance region, in combination with substantial progress made over the last twenty years in determining the scaling behavior of deep inelastic structure functions with both lepton and neutrino probes, enables us to revisit local duality in detail. Within the aforementioned assumption that higher-twist effects are small if averaged over the full resonance region, the F_2 data we will present can be interpreted as indicating a suppression of sea-quark contributions.

We accumulated data in the nucleon resonance region, $1 < W^2 < 4$ (GeV/c)^2, for both hydrogen and deuterium targets [10]. Measurements in the elastic region were included in the data to verify our absolute normalizations to better than 2%. The data were obtained in Hall C at Jefferson Lab (JLab), using electron beam energies between 2.4 and 4 GeV. Incident beam currents between 20 and 100 μA were used on 4 and 15 cm long targets. Scattered electrons were detected in both the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS), each utilized in a single arm mode to measure the inclusive cross sections. At all beam energy-scattering angle combinations, the central momentum of the spectrometers was varied to cover the full resonance region. The change in central momentum was kept smaller than the momentum acceptance of each spectrometer, to ensure that overlapping data were accumulated. The internal consistency of the data, within a 16% momentum acceptance bite for HMS and a 30% momentum acceptance bite for SOS, was found to be always better than 3%. The Q^2 range covered by our data set is between 0.3 and 5 (GeV/c)^2. We accumulated of order 10^5 counts for every beam energy-scattering angle combination (9 in total for hydrogen, 8 for deuterium). In all cases, the overall systematic uncertainty in the measured cross sections due to target density, beam charge, beam energy, spectrometer acceptance, radiative corrections, and detection efficiency is less than 3% and larger than the statistical uncertainties.

We extracted the structure function F_2 from the measured differential cross sections $\sigma = \frac{d^2\sigma}{d\Omega dE}$ like $F_2 \sim \sigma \times (1+R)/(1+\epsilon R)$ [11]. Here ϵ is the virtual-photon polarization and R is the ratio of longitudinal to transverse cross sections. We used a value of $R = 0.2$ for the present analysis, but the results are consistent within 2% if a parametrization of this quantity based on deep inelastic scattering data at moderate Q^2 is utilized [12]. However, we note that this quantity is presently only known at the $\pm 100\%$ level in the nucleon resonance region above $Q^2 \approx 1$ (GeV/c)^2 [13].

The extracted F_2 data in the nucleon resonance region are shown in Fig. 1a for the hydrogen target, and in Fig. 1b for the deuterium target, as functions of the Nachtmann scaling variable ξ. These figures also include some low Q^2 data from SLAC [14,15]. In terms of the Nachtmann variable $\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$ [16], where M is the nucleon mass, a pattern of scaling violations has been formulated within a QCD framework [3,4]. The variable ξ takes target-mass corrections into account, necessary as the quarks can not be treated as massless partons for low to moderate momentum transfers. Note that, for low x or large Q^2, the scaling variable ξ is almost identical to the Bjorken scaling variable x.

It is clear from Fig. 1 that indeed the data oscillate around an average scaling curve. This suggests that the higher-twist terms in the *averaged* kinematic region are still small [3,4]. The curves shown represent the average scaling curve extracted from our data (solid), and a global fit to the world's deep inelastic data [17] for a fixed $Q^2 = 10$ (GeV/c)^2 (NMC10, dashed), and, in Fig. 1a, for a fixed $Q^2 = 2$ (GeV/c)^2 (NMC2, dot-dashed). Whereas the difference between the NMC fit for fixed $Q^2 = 10$ (GeV/c)^2 and $Q^2 = 2$ (GeV/c)^2 is small, and expected from logarithmic scaling violations, the difference between these NMC fits and our data (with $Q^2 \approx 0.3$ (GeV/c)^2) derived from the duality-averaged scaling curve is dramatic at low ξ. Clearly, the Q^2 dependence of F_2 in this low ξ region is a signature of non-perturbative effects.

We display in the deuterium case (Fig. 1b), the *input* distributions at $Q^2 = 0.34$ (GeV/c)^2 for the next-to-leading order calculations of Glück, Reya and Vogt (GRV, dot-dashed) [18]. In the GRV model, the shape of the gluon and quark-antiquark sea seen by experiment is dynamically generated through gluon bremsstrahlung. As an example, although no strange sea is assumed at the finite Q^2 value for the input distribution, the strange sea carries a finite fraction of the nucleon's momentum at $Q^2 \simeq 10$ (GeV/c)^2, not in disagreement with measured values [6,19,20]. The GRV input distribution has been fixed by assuming only valence and valence-like (the input sea quark distributions also approach zero as $x \to 0$) quark distributions at a finite Q^2 value, constrained with appropriate Q^2-evolutions to SLAC, NMC, and BCDMS [12,21,22] deep inelastic F_2 data at $Q^2 = 5$ (GeV/c)^2. The dotted curves in Figs. 1a and 1b denote the GRV input distributions reflecting *only* their valence quark distributions (i.e. there are no sea quark contributions at all). At large ξ, the discrepancy between the GRV input distributions (at $Q^2 = 0.34$ (GeV/c)^2) and the data can be attributed to the logarithmic scaling violations. Although in the very low Q^2 region below 1 (GeV/c)^2 non-perturbative higher-twist contributions are expected to become relevant [23], the similarity of the input distributions of Ref. [18] and the average scaling curve given by the nucleon resonance data suggests that the duality-averaged scaling curve is dominated by valence-quark or valence-like quark contributions.

To verify this, we show in Fig. 2 a comparison of the averaged scaling curve from the deuterium resonance data (solid curve) with a selection of the world's data for the xF_3 structure function. The xF_3 structure function can be accessed by deep inelastic neutrino-iron scattering [24,25], and is associated with the parity-violating term in the hadronic current. Thus xF_3 measures in the quark-parton model the difference between quark and anti-quark distributions, and is to first order insensitive to sea quark distributions. To enable a direct comparison we have multiplied our average scaling curve by a factor of 18/5 to account for the quark charges, and have applied a straightforward nuclear correction to the xF_3 data to obtain neutrino-deuterium data [26]. Although the agreement between the averaged F_2 scaling curve of the deuterium resonance region and the deep inelastic neutrino xF_3 data is not perfect, the similarity is striking. The observation of Bloom and Gilman that there may be a common origin between the electroproduction of resonances and deep inelastic scattering seems to be true for even the lowest values of Q^2 if one assumes sensitivity to a valence-like quark distribution only.

A possible interpretation for the strong Q^2 dependence of F_2 at low ξ and Q^2 could be that, at very low Q^2, the large-wavelength probe is insensitive to coherent quark-antiquark pairs. In deep inelastic scattering data, which for $\xi \simeq 0.1$ is typically at $Q^2 > 1$ (GeV/c)^2, the dramatic effect of the sea is already noticeable. The effect is further illustrated in Fig. 3. Here, the shaded bands indicate the range of data and uncertainty in existing high-precision deep inelastic measurements of F_2 [12], at selected values of small x. The closed symbols represent the data extracted from this work, utilizing the averaged proton F_2 scaling curve. The error bars here reflect the range in the x and Q^2 value we use to obtain the scaling curve value at a certain ξ. The open symbols are values of F_2 we extracted from Ref. [15]. These data are measured at invariant masses $W^2 > 4$ (GeV/c)^2, and at low Q^2 values ($Q^2 < 1$ (GeV/c)^2). We have assigned an uncertainty of 8% to these data, reflecting both the uncertainty in our extraction procedure and the normalization uncertainty of these older SLAC data. The data agree well with the shaded band of the more recent high-precision SLAC data. For these x values, the high-W^2, low-Q^2, SLAC data exhibit a Q^2 dependence of the F_2 structure function similar as we see in our data. The combined data sample allows the conclusion that the observed effect is first order independent of the W^2 region.

The solid lines in Fig. 3 are just to guide the eye, and connect our datum at $x = 0.14$ with the SLAC data, and, for other values of x, have just been offset with the factor multiplying F_2 for various x. The slopes of these lines are consistent with an $F_2 = 0.33\sqrt{Q}$ behavior. However, it is possible that we just see an apparent $F_2 \sim\sqrt{Q}$ behavior in the limited Q^2 region of our data, transcending the area between scaling at $Q^2 > 1$ (GeV/c)^2 and the $F_2 \sim Q^2$ expectation at $Q^2 \to 0$ [8]. This would be consistent with the rise of deep inelastic F_2 data as a function of Q^2 as shown in Ref. [15]. More data are needed to investigate this point in detail. The dashed lines indicate the Q^2 evolution of F_2 starting from the valence-like (i.e. the input sea quark contributions are included but approach zero as $x \to 0$) input distributions of GRV [18,27]. It is clear that the calculations overshoot the low Q^2 data, indicating the presence of a non-perturbative mechanism reducing the measured F_2 structure function. In contrast, F_2 data extracted from our averaged proton scaling curve at larger ξ (and thus larger Q^2) would be consistent with just a logarithmic Q^2-evolution [10].

The invisibility of coherent quark-antiquark pairs to a low-momentum transfer electron probe would be consistent with other recent results. A similar, although not so obvious, effect can be seen in the Fermilab E665 deep inelastic muon-proton scattering data at $x \approx 0.01$ [28]. The mechanism may also explain the "turn-over" of the $dF_2/d\ln Q^2$ logarithmic slope at very low x ($< 3\times10^{-4}$) exhibited by the ZEUS Collaboration data [31], since this data corresponds to a similar low Q^2 region. Furthermore, recent parity violation results at $Q^2 \leq 0.5$ (GeV/c)^2 [29,30] can be interpreted as being insensitive to the strange sea if the strange and anti-strange quarks in the nucleon exactly cancel. Our data suggest that, if there are sea-quark contributions at these momentum transfers, they may follow the behavior of the valence quarks.

In summary, we have measured inclusive electron-nucleon scattering cross sections in the resonance region for both hydrogen and deuterium targets, and have extracted the structure function F_2 from these. The F_2 data oscillate around average scaling curves, down to the lowest momentum transfers measured. These average F_2 scaling curves resemble deep inelastic xF_3 structure function data, indicating a lack of sensitivity to sea quarks. The momentum-transfer dependence of the F_2 structure function at small x may be consistent with a turn-on of sensitivity to sea quarks.

We acknowledge the outstanding work of the staff of the accelerator division at the Thomas Jefferson National Accelerator Facility in delivering the high quality electron beam. R.E. and C.E.K. want to thank J. Gomez, N. Isgur, and S. Liuti for helpful discussions. This work is supported in part by research grants from the U.S. Department of Energy and the U.S. National Science Foundation.

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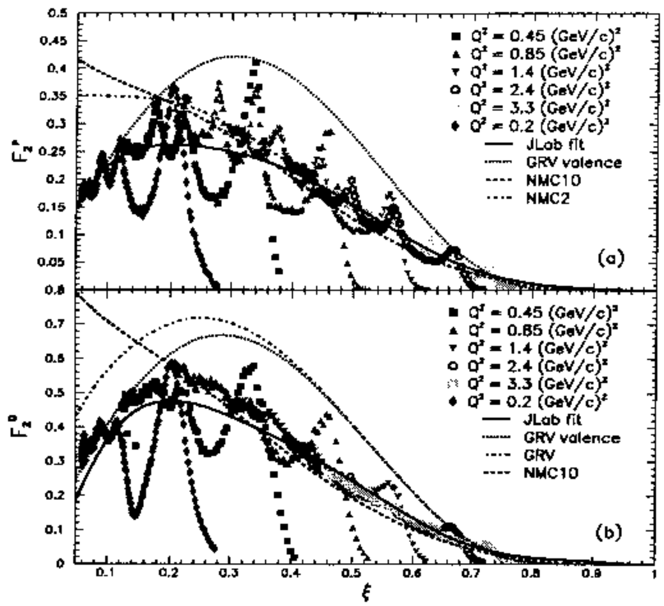

FIG. 1. Extracted F_2 data in the nucleon resonance region for hydrogen (a) and deuterium (b) targets, as functions of the Nachtmann scaling variable ξ. New data from JLab have been extended with high-precision SLAC data. For clarity, only a selection of the data is shown here. The solid curves indicate the scaling curves obtained by averaging over all the nucleon resonance data. The dashed curves indicate the result of the NMC fit to deep inelastic data for a fixed $Q^2 = 10$ (GeV/c)^2. In (a), the dot-dashed curve shows the result of the NMC fit for a fixed $Q^2 = 2$ (GeV/c)^2. In (b), the dot-dashed curve shows F_2 obtained from the input valence-like quark distributions (i.e. valence and sea quarks) of Ref. [18]. Similarly, the dotted curves show F_2 obtained from the input valence-quark distributions from Ref. [18] only.

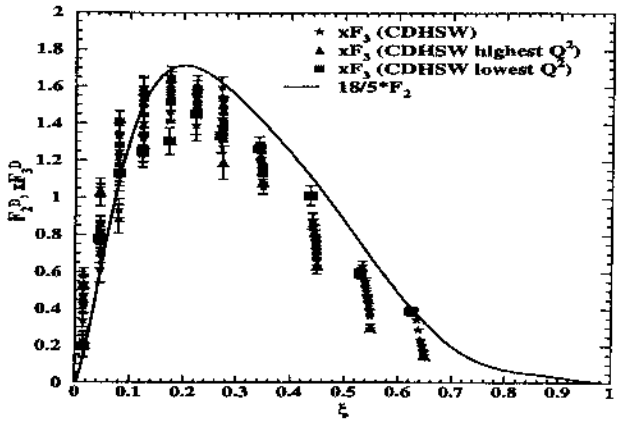

FIG. 2. A comparison of the duality-averaged F_2 scaling curve determined from the nucleon resonance region data with a deuterium target, multiplied by the appropriate factor of 18/5, with the CDHSW data (Ref. [24]) on xF_3 from deep inelastic neutrino-nucleus scattering data, corrected to neutrino-deuterium scattering data. The xF_3 structure function data is to first order sensitive to valence quarks only.

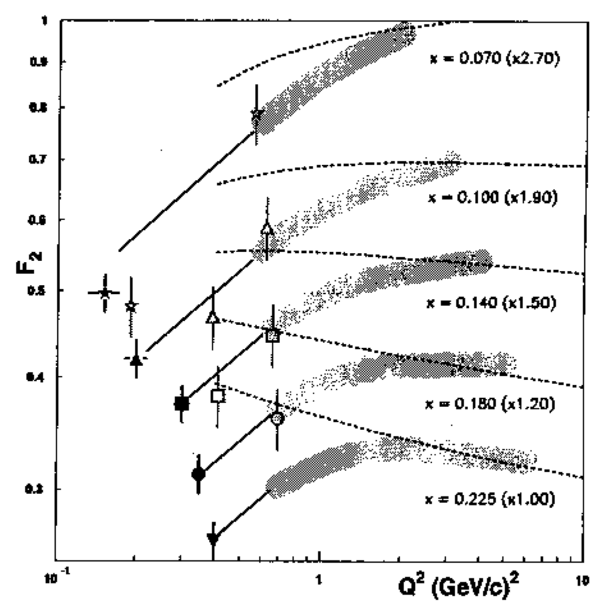

FIG. 3. The low-Q^2 F_2 structure function data for a region in Bjorken x between 0.05 and 0.25. The shaded band indicates the behavior of the high-precision deep inelastic data from Ref. [12]. The closed symbols represent data extracted from the averaged F_2 scaling curve of the proton resonance region. The open symbols represent data extracted from Ref. [15], with $W^2 > 4$ $(\mathrm{GeV/c})^2$. The solid curves are to guide the eye only and represent a $F_2 \sim 0.33\sqrt{Q}$ behavior. The dashed curves denote the Q^2-evolution of F_2 starting with the valence-like input distributions from Ref. [18].