Low-Q scaling, duality, and the EMC effect

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High energy lepton scattering has been the primary tool for mapping out the quark distributions of nucleons and nuclei. Data on the proton and deuteron have shown that there is a fundamental connection between the low and high energy regimes, referred to as quark-hadron duality. We present the results of similar studies to more carefully examine scaling, duality, and in particular the EMC effect in nuclei. We extract nuclear modifications to the structure function in the resonance region, and for the first time demonstrate that nuclear effects in the resonance region are identical to those measured in deep inelastic scattering.

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Extensive measurements of inclusive lepton-nucleus scattering have been performed in deep inelastic scattering (DIS) kinematics. In DIS kinematics, where both the four-momentum transfer, Q, and the energy transfer, ν, are sufficiently large, the extracted structure function exhibits scaling, *i.e.* is independent of Q^2 except for the well understood logarithmic QCD scaling violations. In this region, the structure function is interpreted as an incoherent sum of quark distribution functions, describing the motion of the quarks within the target.

Such measurements have unambiguously shown that the nuclear structure functions deviate from the proton and neutron structure functions. Such modifications, termed the EMC effect after the first experiment to observe them [1], demonstrate that the nuclear quark distribution function is not just the sum of the proton and neutron quark distributions. Within two years of the first observation, over 300 papers were published on the topic. There are now thousands, and yet the effect remains a mystery. For an extensive review of the data and models of the EMC effect, see Ref. [2]

Existing measurements of the EMC effect indicate little Q^2-dependence, and an A-dependence in the magnitude, but not the overall form, of the structure function modification in nuclei. The nature of the modifications in nuclei depends primarily on Bjorken-x ($= Q^2/2M\nu$), which in the parton model is interpreted as the momentum fraction of the struck quark, and the nuclear effects are divided into four distinct regions. In the shadowing region, $x < 0.1$, the structure function is decreased in nuclei relative to the expectation for free nucleons. In the anti-shadowing region, $0.1 < x < 0.3$, the structure function shows a small nuclear enhancement. For $0.3 < x < 0.7$, referred to as the EMC effect region, the nuclear structure function shows significant depletion. Finally, there is a dramatic enhancement as x increases further, resulting from the increased Fermi motion of the nucleons in heavier nuclei.

Explanations of the EMC effect are hampered by the lack of a single description that can account for the nuclear dependence of the quark distributions in all of these kinematic regimes. Here, we will limit ourselves to $x > 0.3$, the region where valence quarks dominate. We note that, although the EMC effect has been mapped out over a large range of x, Q^2, and A, information is still rather limited in some regions. There are limited data on light nuclei ($A < 9$), and almost no data at extremely large x, where the quark distributions in nuclei are enhanced relative to the distributions in nucleons.

Even limiting ourselves to $x > 0.3$, there is not a single explanation that can completely account for the observed nuclear structure function modifications. If the nuclear structure function in this region is expressed as a convolution of proton and neutron structure functions, there are two alternative approaches used to describe the observed medium effect: (1) incorporating nuclear physics effects that modify the energy-momentum behavior of the bound proton with respect to the free proton, or (2) incorporating changes to the internal structure of the bound proton. Recently, it was concluded that the binding of nucleons alone can not explain the EMC effect [3], and that explicit mesonic components appear to be insufficient due to limits set by Drell-Yan measurements [4]. Hence, the EMC effect may be best described in terms of modifications to the internal structure of the nucleon when in the nuclear environment.

Inspired by a recent series of electron scattering experiments in Hall C at Jefferson Lab, we revisit the issues of scaling in nuclear structure functions and the EMC effect. The Hall C data are at lower invariant mass W, $W^2 = M_p^2 + 2M_p\nu(1-x)$, and therefore higher x, than data thus far used to investigate the EMC effect. Most notably, these new data are in the resonance region. In the DIS region, the Q^2-dependence of the structure func-

tions is predicted by perturbative QCD (pQCD), while additional scaling violations, termed higher twist effects, occur at lower Q^2 values. Thus, data in the resonance region would not naively be expected to manifest the same EMC effect as data in the deep inelastic scaling regime ($W^2 > 4$ GeV^2). The effect of the nuclear medium on resonance excitations seems non-trivial, and may involve much more than just the modification of quark distributions observed in DIS scattering from nuclei.

However, while resonance production may show different effects from the nuclear environment, there are also indications that there is a deeper connection between inclusive scattering in the resonance region and in the DIS limit. This connection has been a subject of interest for nearly three decades since quark-hadron duality ideas, which successfully described hadron-hadron scattering, were first extended to electroproduction. In the latter, Bloom and Gilman [5] showed that it was possible to equate the proton resonance region structure function $F_2(\nu, Q^2)$ (at some low Q^2 value) to the DIS structure function $F_2(x)$ in the high-Q^2 scaling regime, where F_2 is simply the incoherent sum of the quark distribution functions. For electron-proton scattering, the resonance structure functions have been demonstrated to be equivalent on average to the DIS scaling strength for all of the spin-averaged structure functions (F_1,F_2,F_L) [6, 7], and for some spin-dependent ones (A_1) [8].

The goal of this paper is to quantify whether similar quark-hadron duality ideas play a role in nuclear structure functions and, if so, to what extent this can be utilized to access poorly understood kinematic regimes. While the measurements of duality from hydrogen indicate that the resonance structure function are on average equivalent to the DIS structure functions, it has been observed that in nuclei, this averaging is performed by the Fermi motion of the nucleons, and so the resonance region structure functions yield the DIS limit without any additional averaging [9, 10].

Figure 1 shows the structure functions for hydrogen [6], deuterium [11], and iron [10], compared to structure functions from MRST [12] and NMC [13] parameterizations. Each set of symbols represents data in a different Q^2 range, with the highest Q^2 curves covering the highest ξ values. Note that the data are plotted as a function of the Nachtmann variable, $\xi = 2x/(1+\sqrt{1+4M^2x^2/Q^2})$, rather than x. In the limit of large Q^2, $\xi \to x$, and so ξ can also be used to represent the quark momentum in the Bjorken-limit. At finite Q^2, the use of ξ reduces scaling violations related to target mass corrections [14]. The difference between ξ and x is often ignored in high energy scattering or at low x, but cannot be ignored at large x or low Q^2.

The transition from scaling on average in the proton to true scaling for nuclei is clearly visible. There is significant resonance structure visible in hydrogen, but on average the structure function reproduces the scaling curve to

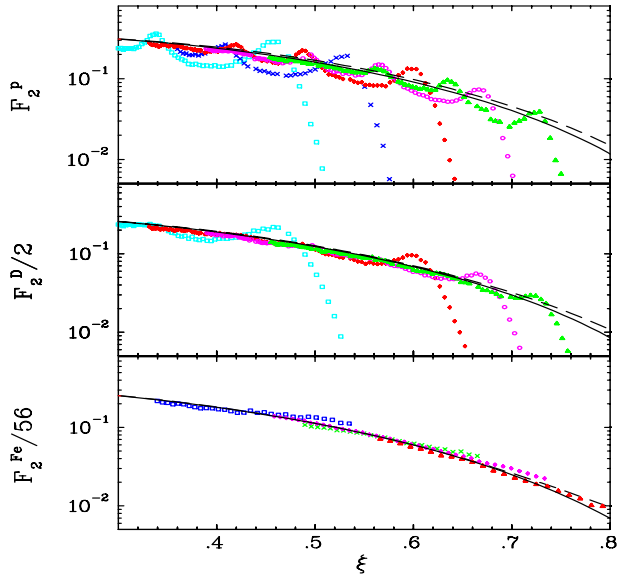

FIG. 1: The F_2 structure function per nucleon vs ξ for hydrogen (top), deuterium (middle), and iron(bottom). For the hydrogen and deuterium data ($0.8 < Q^2 < 3.3$ GeV^2), the elastic (quasielastic) data have been removed. For the iron data ($Q^2 < 5.0$ GeV^2), a cut of $W^2 > 1.2$ GeV^2 is applied to remove the quasielastic peak. The curves are the MRST [12] (solid) and NMC [13] (dashed) parameterizations of the structure functions, with a parameterization of the EMC effect [15] applied to produce the curve for iron. (Color online)

better than 5% for $Q^2 > 1$ GeV^2 [6]. For deuterium, the Fermi motion broadens the resonances to the point where only the Δ resonance has a clear peak, and the data at higher W^2 values, while still in the resonance region, is indistinguishable from the scaling curve except at the lowest Q^2 values. For the iron data, taken at somewhat higher Q^2 values, even the Δ is no longer prominent, and deviations from pQCD predictions are small, and limited to the tail of the quasielastic peak.

Figure 2 shows the structure function per nucleon for deuterium as a function of Q^2 at several values of ξ. Above $W^2 = 4$ GeV^2, the data are in the DIS region and the Q^2-dependence is consistent with QCD evolution of the structure function, as indicated by the dashed lines. However, the data do not show significant deviations from scaling as we enter the resonance region. Above $Q^2 = 3$ GeV^2, the data deviate from the logarithmic Q^2-dependence (dashed lines) by $\lesssim 10\%$, even for $W^2 < 2$ GeV^2. Data on heavier nuclei also show this extended scaling in the resonance region [10].

The data indicate relatively small deviations from pQCD for $Q^2 > 3$ GeV^2 at all values of ξ measured. These deviations decrease as Q^2 increases, making the nuclear structure functions at large ξ consistent with the perturbative dependence even at values of W^2 well below the typically DIS limit. Analyses of duality for the proton [17] and for nuclei [18] show that the moments of

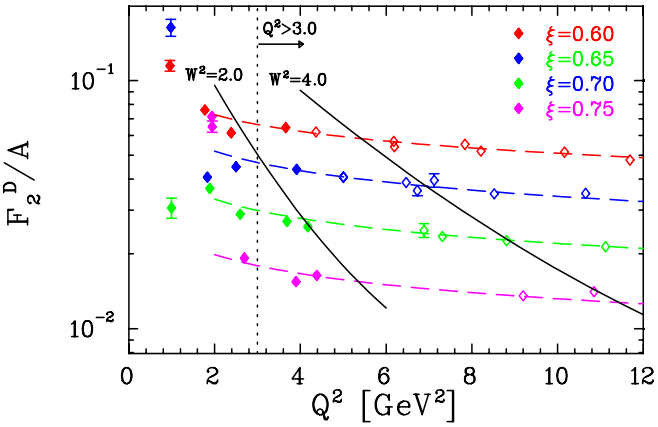

FIG. 2: F_2 structure function per nucleon vs. Q^2 for deuterium at fixed values of ξ. Dashed lines show a logarithmic Q^2 dependence, with $dF_2/d\ln Q^2$ determined from SLAC data at high Q^2 (up to 20 GeV^2). The solid lines denote W^2=2.0 and 4.0 GeV^2. The combined statistical and systematic uncertainties are shown. The hollow symbols are data from SLAC [16], while the solid symbols are from Jefferson Lab [10]. (Color online)

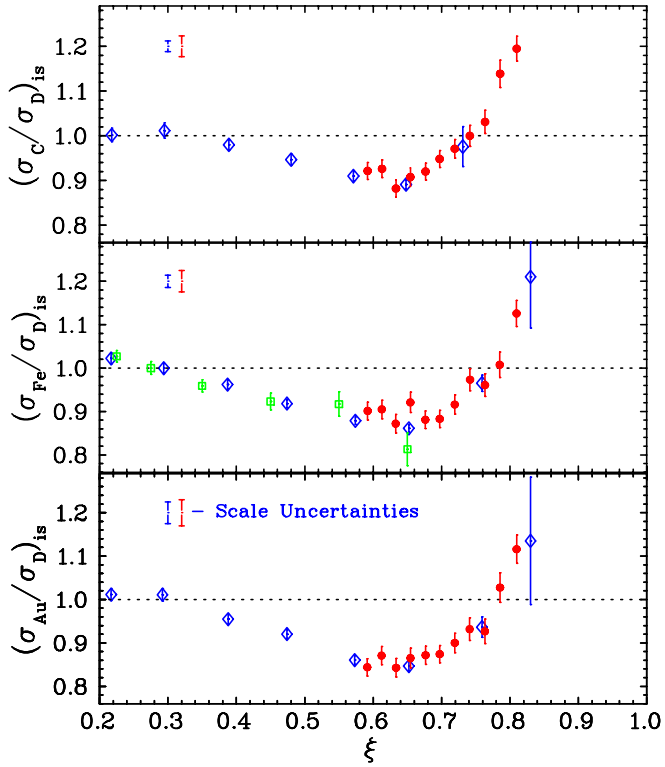

FIG. 3: Ratio of nuclear to deuterium cross section per nucleon, corrected for neutron excess. The solid circles are Jefferson lab data taken in the resonance region ($1.2 < W^2 < 3.0$ GeV^2, $Q^2 \approx 4$ GeV^2). The hollow diamonds are SLAC E139 data, and the hollow squares are BCDMS data, both taken in the DIS region. The scale uncertainties for the SLAC (left) and JLab (right) data are shown in the figure. (Color online)

the structure function, $M_n = \int x^{n-2} F_2(x, Q^2) dx$ is the nth moment, follow perturbative QCD evolution down to $Q^2 \approx 2$ GeV^2 for the proton and to even lower values, $Q^2 \lesssim 1$ GeV^2, for nuclei. The fact that the moments follow the perturbative behavior is consistent with the observation that the structure function in Figs. 1 and 2 are, on average, in agreement with the perturbative structure function. Above $\xi = 0.75$, it is difficult to quantify the deviations from pQCD behavior as there is little data in the DIS region on which to base perturbative structure function predictions.

JLab experiment E89-008 [10, 19] measured inclusive cross sections from deuterium, carbon, iron, and gold. For this data, we take the cross section ratio of iron to deuterium *in the resonance region* for the highest Q^2 measured ($Q^2 \sim 4$ GeV^2), requiring $W^2 > 1.2$ GeV^2 to exclude the region very close to the quasielastic peak. Figure 3 shows the cross section ratio of heavy nuclei to deuterium for the previous SLAC E139 [15] and BCDMS [20] DIS measurements, and for the JLab data in the resonance region. Coulomb corrections were applied in the analysis of the JLab data [19], but not the SLAC data. The SLAC results shown here have been modified to include Coulomb corrections. The corrections are determined by applying an offset to the incoming and outgoing electron energy at the reaction vertex, due to the Coulomb field of the nucleus. The correction factor is <0.5% for carbon, and 1.5-2.5% for gold. The size and ξ-dependence of nuclear modifications in the JLab data agrees with the higher Q^2, W^2 data for all targets.

The data obtained here provide a significant improvement in the measurements at large ξ. In this region, the modifications are dominated by the effects of binding and Fermi motion. Because binding can influence the structure function for all ξ values, it is important to constrain the effects of binding with this large-ξ data, so that a more precise extraction of more exotic nuclear effects can be made at lower ξ values.

A careful examination of the crossover point at large ξ, where the ratio $(\sigma_A/\sigma_D)_{is}$ becomes larger than unity, reveals that this occurs at larger ξ for heavy nuclei than for light nuclei. This seems to contradict the argument that the dramatic enhancement at large ξ is due to increased Fermi motion in heavier nuclei. Within the convolution formula of proton and neutron structure functions, this crossover comes about due to counteracting contributions at large ξ of the average nucleon binding energy and average kinetic energy [21], and is hardly expected to change for $A > 10$. However, the effect we observe was predicted in a calculation by Gross and Liuti [22] using a manifestly covariant form of the convolution formula, with the most significant difference being an additional binding correction due to the explicit dependence of the bound nucleon structure function on the momentum of the bound nucleon. In their calculation, the crossover point occurs at

smaller ξ values for carbon than for heavier nuclei.

The agreement of the resonance region data with the DIS measurement of the EMC effect, which directly measures the modification of quark distributions in nuclei, is quite striking. There is no *a priori* reason to expect that the nuclear effects in resonance production would be similar to the effects in scattering from quarks. However, it can be viewed as a natural consequence of the quantitative success of quark-hadron duality [6]. As seen in Fig. 1, the structure functions for nuclei show little deviation from pQCD, except in the region of the quasielastic peak (and Δ resonance at low Q^2). As Q^2 increases, the deviations from pQCD decrease as quasielastic scattering contributes a smaller fraction of the cross section. In retrospect, given the lack of significant higher twist contributions, combined with the fact that any A-independent scaling violations will cancel in the ratio, it is perhaps not surprising that the resonance EMC ratios are in agreement with the DIS measurements.

This increase in the region of scaling opens up possibilities to further extend measurements for large ξ and low A. Existing data for the EMC effect at high ξ are limited because of the usual DIS cuts applied to the data which require $Q^2 > 15$ (36) GeV^2 for $\xi = 0.8$ (0.9). These high Q^2 values yield dramatically smaller cross sections, further reduced by the rapidly falling quark distributions at large ξ. Thus, no facility has the combination of energy and luminosity necessary to make precise measurements of these nuclear effects at large ξ in the DIS region.

The ability to measure the EMC effect at reduced Q^2 values will be especially important for for light nuclei where low target densities, *e.g.*, ^{3}He and ^{4}He, or limitations on the beam current that can be applied to the target, *e.g.*, ^{7}Li, further limit measurements in the DIS region. These light nuclei are of special interest because models of the EMC effect can be evaluated in light nuclei without some of the uncertainties in the nuclear structure of the heavier nuclei. In addition, the ξ-dependence of the EMC effect may be very different in few-body nuclei, which is not well constrained by existing data. For example, while the calculations of Ref. [22] predict that the high-ξ crossover point in carbon occurs at lower ξ than in heavier nuclei, they predict a crossover at much larger ξ for ^{4}He. Similarly, Ref. [23], predicts a different high-ξ behavior in ^{4}He than in heavy nuclei, as well as a significant difference between ^{3}He and ^{4}He. Finally, because there are no free neutron targets, nuclear effects in light nuclei must be well understood to extract reliable information about neutron structure from measurements on deuterium and ^{3}He.

Future measurements at Jefferson Lab [24] will make full use of the expanded kinematic coverage resulting from this extended scaling in nuclei. They will extend measurements of the EMC effect to larger ξ values and to few-body nuclei. Based on the results shown here, the uncertainties on extracting the nuclear dependence of the quark distribution at large ξ due deviations from pQCD behavior due to higher twist contributions will be small, if not negligible, compared to the uncertainties of existing data in the large-ξ regime.

In conclusion, we present the first extraction of the nuclear dependence of the inclusive structure function in the resonance region. The data are in agreement with previous measurements of the nuclear dependence of the quark distributions in DIS scattering measurements of the EMC effect. This surprising result can be understood in terms of quark-hadron duality, where the structure function in the resonance regime is shown to have the same perturbative QCD behavior as in the DIS regime. These data expand the ξ and Q^2 range for the EMC effect measurements, and provide the first new measurement of the EMC effect for a decade. It also indicates the possibility for dramatic improvements in both the ξ- and A-range in future measurements, using the higher beam energies currently available at Jefferson Lab.

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[1] J. Aubert et al., Phys. Lett. B **123**, 275 (1983).
[2] D. F. Geesaman, K. Saito, and A. W. Thomas, Ann. Rev. Nucl. Sci. **45**, 337 (1995).
[3] J. R. Smith and G. A. Miller, Phys. Rev. **C65**, 055206 (2002).
[4] D. M. Alde et al., Phys. Rev. Lett. **64**, 2479 (1990).
[5] E. Bloom and F. Gilman, Phys. Rev. D **4**, 2901 (1971).
[6] I. Niculescu et al., Phys. Rev. Lett. **85**, 1186 (2000).
[7] Y. Liang, Ph.D. thesis, American University (2002).
[8] A. Airapetian et al. (HERMES), Phys. Rev. Lett. **90**, 092002 (2003).
[9] B. W. Filippone et al., Phys. Rev. C **45**, 1582 (1992).
[10] J. Arrington et al., Phys. Rev. C **64**, 014602 (2001).
[11] I. Niculescu, Ph.D. thesis, Hampton University (1999).
[12] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Eur. Phys. J. **C28**, 455 (2003).
[13] M. Arneodo et al. (New Muon.), Phys. Lett. **B364**, 107 (1995).
[14] H. Georgi and H. D. Politzer, Phys. Rev. D **14**, 1829 (1976).
[15] J. Gomez et al., Phys. Rev. D **49**, 4348 (1994).
[16] S. Dasu et al., Phys. Rev. D **49**, 5641 (1994).
[17] C. S. Armstrong et al., Phys. Rev. **D63**, 094008 (2001).
[18] G. Ricco et al., Phys. Rev. C **57**, 356 (1998).
[19] J. Arrington et al., Phys. Rev. Lett. **82**, 2056 (1999).
[20] A. C. Benvenuti et al. (BCDMS), Phys. Lett. **B189**, 483 (1987).
[21] S. A. Kulagin, G. Piller, and W. Weise, Phys. Rev. **C50**, 1154 (1994).
[22] F. Gross and S. Liuti, Phys. Rev. **C45**, 1374 (1992).
[23] V. V. Burov, A. V. Molochkov, and G. I. Smirnov, Phys. Lett. **B466**, 1 (1999).
[24] J. Arrington et al., Jefferson Lab E00-101 (2000).