PHYSICAL REVIEW C VOLUME 45, NUMBER 4 APRIL 1992

Nuclear structure functions at $x > 1$

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(Received 19 April 1991)

Nuclear structure functions are extracted for high-energy electron scattering from nuclei at large values of the kinematic variable x and Q^2 in the range 1–4 $(\mathrm{GeV}/c)^2$. At the highest Q^2, the data for $x > 1$ begin to display a scaling indicative of local duality.

PACS number(s): 25.30.Fj, 13.60.Hb

Deep inelastic scattering (DIS) of electrons has proven to be a powerful tool in understanding the structure of the nucleon in terms of its constituents. In the parton model, the deep inelastic structure functions can be related to the longitudinal momentum distribution of the quarks in the limit where both the electron energy transfer ν and the square of the four-momentum transfer $Q^2 \to \infty$. In this limit, the structure functions display scaling, i.e., they possess little dependence on Q^2. The remaining dependence on the kinematic variable $x = Q^2/2M\nu$, with M the nucleon mass, yields the quark momentum distributions where x is interpreted as the longitudinal momentum fraction of the quarks. For a nucleon target, x varies from 0 to 1, while for a nuclear target with mass A, x can vary from 0 to A.

The behavior of the nucleon structure functions as $x \to 1$ has been shown by Drell and Yan [1] and West [2] to connect smoothly with the elastic nucleon form factors. In addition, Bloom and Gilman [3] discovered that, in the resonance region, the resonance form factors fall with Q^2 at the same rate as the scaling structure functions. They observed that the resonance peaks seen at low Q^2 could be averaged over a finite range in x (i.e., locally) to yield the high Q^2 deep inelastic structure functions. This duality between the scaling structure functions and the elastic and resonance form factors was initially discussed in a simple parton model [4]. DeRujula, Georgi, and Politzer [5] showed that this local duality was expected from perturbative QCD and should also be valid for the nucleon elastic peak at $x = 1$ if the structure functions were analyzed in terms of the Nachtmann variable $\xi = 2x/[1+(1+4M^2x^2/Q^2)^{1/2}]$. This variable is the correct variable [6] in which to study scaling violations at finite Q^2 and accounts for the finite target mass M. In this picture the elastic peak and resonances do not "disappear" into the DIS continuum but instead move to larger ξ, while maintaining a nearly constant strength with respect to the DIS structure functions, which fall rapidly with increasing ξ. For the nucleon, this local duality allows the logarithmic Q^2 dependence (scaling violations), and the stronger m^2/Q^2 dependence (higher twist effects) of the structure functions to be studied [5] in a Q^2 regime where the effects are larger and hence easier to measure.

When the nuclear structure functions were initially investigated, it was expected that the result would be simply related to that for A nucleons. However, with the observation that the nuclear structure functions (for $x < 1$) are not simply related to the free nucleon structure functions [7–9] it became clear that the nuclear medium has a nontrivial effect on the structure of the nucleon. Any complete explanation for these effects must also describe the nuclear structure function at $x > 1$. In order to provide additional data with which to test the models, and to explore for the first time in nuclei the connections discussed above between the large x behavior of the scaling structure functions and the resonance and elastic form factors, we have extracted the nuclear structure function νW_2 from high-energy electron scattering from nuclei with A ranging from 4 to 197.

The experiment was performed at the Stanford Linear Accelerator Center Nuclear Physics Facility (NPAS), where the Nuclear Physics Injector provided electron beams from 2 to 4 GeV. The data were taken with targets of ^{4}He, C, Al, Fe, and Au, with the most extensive

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data taken with the Fe target. Details of the experiment have been described previously [10] and only the elements unique to the extraction of νW_2 will be discussed here.

The inclusive differential cross section for electron scattering from nuclei can be expressed in the one-photon-exchange approximation as

$$\frac{d^2\sigma}{d\Omega\, d\nu} = \sigma_{\rm Mott}[W_2^A + 2W_1^A \tan^2(\theta/2)] ,$$

where $\sigma_{\rm Mott} = 4\alpha^2 E^2 \cos^2(\theta/2)/Q^4$, E' is the scattered electron energy, and θ is the electron scattering angle. In general W_2^A and W_1^A are functions of two kinematic variables, e.g., Q^2 and ν. In the parton model it is the functions νW_2 and MW_1 which are expected to scale and to be related to the longitudinal momentum distribution of the quarks.

In order to extract the structure function, νW_2, from the measured cross sections without doing a Rosenbluth separation (i.e., an angular distribution at fixed q^2 and ν) a knowledge of the ratio of cross sections for absorption of longitudinal and transverse virtual photons, $R = \sigma_L/\sigma_T = W_2(1+\nu^2/Q^2)/W_1 - 1$, is required. We can write the structure function in terms of the measured inelastic scattering cross section $\sigma_{\rm tot} = d^2\sigma/d\Omega\, d\nu$ and R as

$$\nu W_2^A = \nu(\sigma_{\rm tot}/\sigma_{\rm Mott})\frac{1}{1+\beta} ,$$

where

$$\beta = 2\tan^2(\theta/2)\frac{(1+Q^2/4M^2x^2)}{(1+R)} .$$

Thus, uncertainties in the assumed value of R can lead to uncertainties in the extracted structure function. However, from the form of the above equations, for forward angles and $R<1$, the dependence of νW_2^A on R is small. Contributions to R in the x range of this experiment can result from Fermi-smeared deep inelastic scattering as well as from quasielastic nucleon scattering. There are new data on R for Fe in the deep inelastic range [11]. These data indicate that $R_{\rm Fe}^{\rm dis} < 0.5$ (with little nuclear mass dependence) for $Q^2 = 1-5$ GeV^2 and $x = 0.2-0.5$. A reasonable description of the data is provided by $R_{\rm Fe}^{\rm dis} = 0.5/Q^2$ with Q^2 in (GeV/c)^2 and with little x dependence. For the quasielastic contribution, an impulse approximation estimate yields $R^{\rm QE} \simeq G_E^2/\tau G_M^2$, where $\tau = Q^2/4M^2$, and G_E, G_M are the nucleon electric and magnetic elastic form factors. A value for $R^{\rm QE} \simeq 0.5/Q^2$ is also consistent (within $\sim 50\%$) with the impulse approximation prediction using the nucleon elastic form factor data for the Q^2 range of the present experiment. We have thus assumed this kinematic dependence for R over the complete range of this experiment, with an uncertainty of 50%. This assumption leads to a worse case contribution to the uncertainty in the extracted value of νW_2^A of $\pm 3\%$.

In order to study the approach to scaling of νW_2^A we consider only data for $Q^2 > 1$ (GeV/c)^2. This is the Q^2 for which scaling is first observed for the nucleon structure functions. The data presented are for incident electron energy $E = 3.595$ GeV with $\theta = 20°$, 25°, 30° for all targets. Additional data were taken at $E = 3.595$ GeV, $\theta = 39°$, and $E = 3.995$ GeV, $\theta = 30°$ for the Fe target alone. Figure 1 shows the structure function per nucleon for Fe as a function of x, for a Q^2 range of 1–4 (GeV/c)^2. The increasing separation of the data for different Q^2 can be attributed to the dominance of quasielastic scattering at larger x. Here the Q^2 dependence is governed by the nucleon elastic form factors $G(Q^2) \sim 1/(1+Q^2/0.71)^2$, with Q^2 in (GeV/c)^2. At lower x, deep inelastic scattering (which should have little Q^2 dependence) becomes more important. Thus we observe the expected dominance of Fermi-smeared deep inelastic scattering at medium x and quasielastic scattering at high x.

However, a completely different picture emerges if we consider νW_2^A vs the Nachtmann variable ξ, using as the characteristic mass, the nucleon mass. This is displayed in Fig. 2 for the same data as in Fig. 1. Here we see that at low ξ the data cluster around a single curve, while at larger ξ they appear to approach this universal curve from below. This is demonstrated in Fig. 3 where $\nu W_2^{\rm Fe}$ vs Q^2 is shown for several values of ξ. Here one sees that larger values of ξ require higher Q^2 in order to begin to

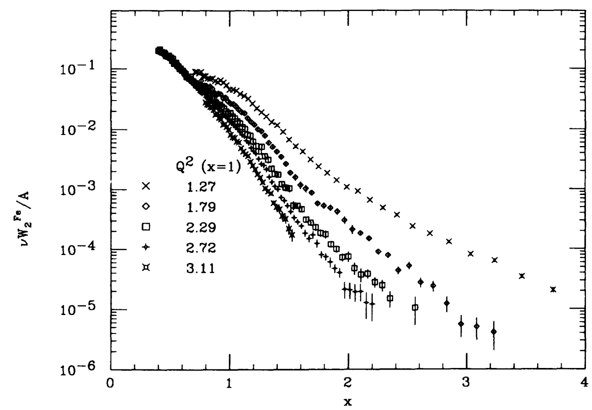

FIG. 1. Measured structure function per nucleon for Fe vs x. The Q^2 value at $x=1$ is also listed for the different kinematics.

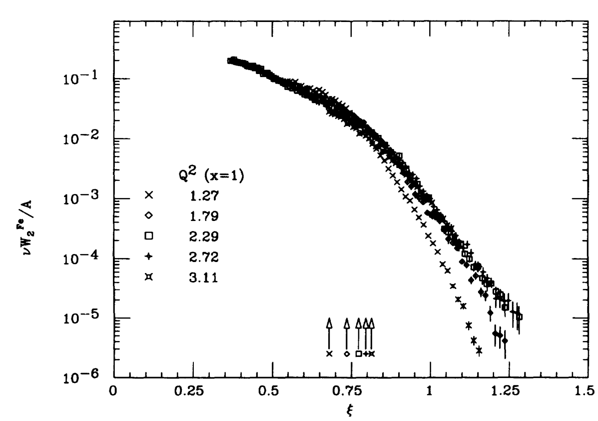

FIG. 2. Measured structure function per nucleon for Fe vs ξ. The arrows indicate the kinematic point $x=1$ for each Q^2.

exhibit the scaling. The lack of a significant A dependence of the scaling in ξ can be seen in Fig. 4, where the structure functions for He, C, and Au are shown. It should be noted, however, that these data were taken over a more limited set of kinematics than for the Fe target.

The observed scaling behavior appears to be consistent with that expected from the local duality arguments discussed earlier. There, suitable local averaging of the structure function over ξ for the elastic peak and nucleon resonances seen at low Q^2 produced a structure function *consistent* with the high Q^2 scaling limit structure function (modulo QCD scaling violations). Here we see indications that the Fermi motion of the nucleons in the nucleus may be performing this "local averaging." Such an averaging could be expected in a simple impulse approximation where the nucleus is composed of moving nucleons interacting only through some average potential. If this picture is indeed correct, one can then extract the large x, scaling limit nuclear structure function from moderate Q^2 [<10 $(\mathrm{GeV}/c)^2$] inclusive scattering without "interference" from quasielastic scattering.

This apparent scaling of the nuclear structure function versus the Nachtmann variable suggests a possible link with another kind of scaling observed in nuclei: y scaling [12,13]. Here, in the simplest picture, the electron-nucleus cross section is divided by the elastic nucleon cross section and a universal function emerges—$F(y)$—which is independent of Q^2 and can be related to the momentum distribution of the nucleons in the nucleus. In this simple impulse approximation picture, $|y|$ is the minimum momentum that the nucleon can possess before the scattering. In the simplest relativistic definition $y=(2M\nu-Q^2)/2q_3$, where q_3 is the three-momentum transfer of the virtual photon. With this approximation we can relate y and ξ: $y=M(1-\xi-\delta)/(1+\delta)$, where $\delta=M^2\xi^2/Q^2$. While this expression does simplify as $Q^2\to\infty$ where $y\to M(1-\xi)$, there is no simple identification for the Q^2 range of this experiment. However, it has recently been demonstrated [14] that in a relativistic impulse approximation $F(y)$ can be interpreted as the nucleon light-cone momentum distribution and y as the light-cone momentum of the nucleon in the nucleus. These authors also show that this is the same function that enters into the convolution formula [15,16] for the nuclear structure functions in calculations of the European Muon Collaboration effect [7–9]. Thus, the scaling of $F(y)$ combined with local duality in the nucleon structure functions can lead to scaling of $\nu W_2(\xi)$ in the convolution picture.

In conclusion, we have extracted the nuclear structure function νW_2^A for $A=4$–197, $Q^2>1$ $(\mathrm{GeV}/c)^2$, and $x\gtrsim 1$. We observe an approach to scaling of νW_2^A when analyzed in terms of the Nachtmann variable. This scal-

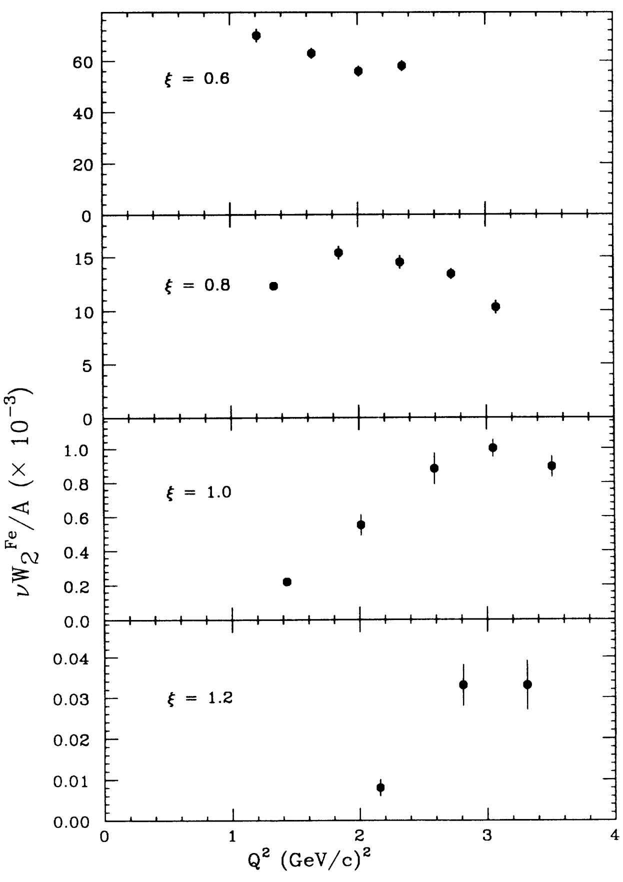

FIG. 3. Structure function per nucleon for Fe vs Q^2 for fixed values of ξ. The data have been interpolated to obtain values at fixed ξ.

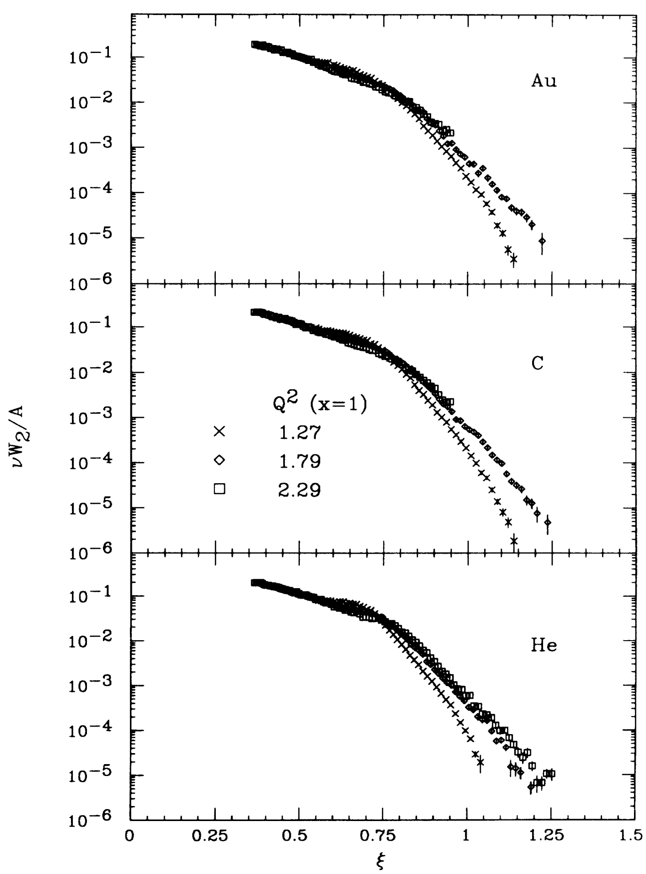

FIG. 4. Structure function per nucleon for He, C, and Au targets vs ξ.

ing appears consistent with QCD predictions of local duality in the structure function. Clearly more data are needed at higher Q^2 and larger ξ in order to determine if this scaling does in fact persist, and to measure the scaling limit structure function if the scaling is observed.

We gratefully acknowledge support from the National Science Foundation, Grant No. PHY88-17296, the U.S. Department of Energy, and the Swiss National Science Foundation. One of us (B.W.F.) acknowledges support from the Alfred P. Sloan Foundation.

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