Nuclear shadowing at low Q^2

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We reexamine the role of vector meson dominance in nuclear shadowing at low Q^2. We find that models incorporating both vector meson and partonic mechanisms are consistent with both the magnitude and the Q^2 slope of the shadowing data.

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There has been renewed interest recently in the problem of nuclear shadowing in structure functions at low and intermediate Q^2. In part, this has been prompted by the analysis of the NuTeV Collaboration [1] of neutrino-nucleus cross sections and subsequent questions about nuclear shadowing corrections when extracting nucleon quark distributions or electroweak parameters [2–4]. Indeed, shadowing in neutrino scattering has received considerably less attention than in electromagnetic reactions, and currently there are proposals to utilize high intensity neutrino and antineutrino beams to perform high statistics measurements of $\nu/\bar{\nu}$-nucleus cross sections at Fermilab [5]. A pressing need exists, therefore, to understand the differences between nuclear shadowing effects in charged lepton and neutrino scattering [6,7], especially at low Q^2.

An extensive review of both data and models of nuclear shadowing was given recently by Piller and Weise [8]. Before one can reliably tackle nuclear corrections in neutrino scattering, however, it is vital to determine the relevant degrees of freedom responsible for shadowing in charged lepton scattering, where data are much more copious. The best available data on nuclear shadowing, including the Q^2 dependence, are from the New Muon Collaboration (NMC) [9–11]. We shall concentrate on a model based on a two-phase picture of nuclear shadowing [12–14], similar to that pioneered by Kwiecinski and Badelek [15–17], which we published just before the release of the final NMC data [11]. For clarity we briefly review this model.

At high virtuality, the interaction of a photon with a nucleus can be efficiently parametrized through a partonic mechanism, involving diffractive scattering through the double and triple Pomeron [18]. For $Q^2 \gtrsim 2\ \mathrm{GeV}^2$, the contribution to the nuclear structure function F_2^A (per nucleon) from this mechanism can be written as

$$\delta^{(\mathbb{P})} F_2^A(x,Q^2) = \frac{1}{A}\int_{y_{min}}^{A} dy\, f_{\mathbb{P}/A}(y) F_2^{\mathbb{P}}(x_{\mathbb{P}},Q^2), \tag{1}$$

where $f_{\mathbb{P}/A}(y)$ is the Pomeron ($\mathbb{P}$) flux, and $F_2^{\mathbb{P}}$ is the effective Pomeron structure function [19]. The variable $y = x(1 + M_X^2/Q^2)$ is the light-cone momentum fraction carried by the Pomeron (M_X is the mass of the diffractive hadronic debris) and $x_{\mathbb{P}} = x/y$ is the momentum fraction of the Pomeron carried by the struck quark. The dependence of $F_2^{\mathbb{P}}$ on Q^2 at large Q^2, in the region where perturbative QCD can be applied, arises from radiative corrections to the parton distributions in the Pomeron [17,20], which leads to a weak, logarithmic, Q^2 dependence for the shadowing correction $\delta^{(\mathbb{P})}F_2^A$. Alone, the $\mathbb{P}$ contribution to shadowing would give a structure function ratio F_2^A/F_2^D that would be almost flat for $Q^2 \gtrsim 2\ \mathrm{GeV}^2$ [21].

On the other hand, the description of shadowing at low Q^2 requires a higher-twist mechanism, such as vector meson dominance (VMD), which can map smoothly onto the photoproduction limit at $Q^2=0$. The VMD model is empirically based on the observation that some aspects of the interaction of photons with hadronic systems resemble purely hadronic interactions [22,23]. In QCD language this is understood in terms of the coupling of the photon to a correlated $q\bar{q}$ pair with low invariant mass, which may be approximated as a virtual vector meson. One can then estimate the amount of shadowing in terms of the multiple scattering of the vector meson using Glauber theory [24]. The corresponding VMD correction to F_2^A is

$$\delta^{(V)} F_2^A(x,Q^2) = \frac{1}{A}\frac{Q^2}{\pi}\sum_V \frac{M_V^4\,\delta\sigma_{VA}}{f_V^2(Q^2+M_V^2)^2}, \tag{2}$$

where $\delta\sigma_{VA}$ is the shadowing correction to the vector meson-nucleus cross section, f_V is the photon-vector meson coupling strength [22], and M_V is the vector meson mass. In practice, only the lowest mass vector mesons ($V=\rho^0,\omega,\phi$) are important at low Q^2. (Inclusion of higher mass states, including continuum contributions, leads to so-called generalized vector meson dominance models [25].) The vector meson propagators in Eq. (2) lead to a strong Q^2 dependence of $\delta^{(V)}F_2^A$ at low Q^2, which peaks at $Q^2 \sim 1\ \mathrm{GeV}^2$, although one should note that the nucleon structure function itself also varies rapidly with Q^2 in this region. For $Q^2 \to 0$ and fixed x, $\delta^{(V)}F_2^A$ disappears because of the vanishing of the total F_2^A. Furthermore, since this is a higher twist effect, shadowing in

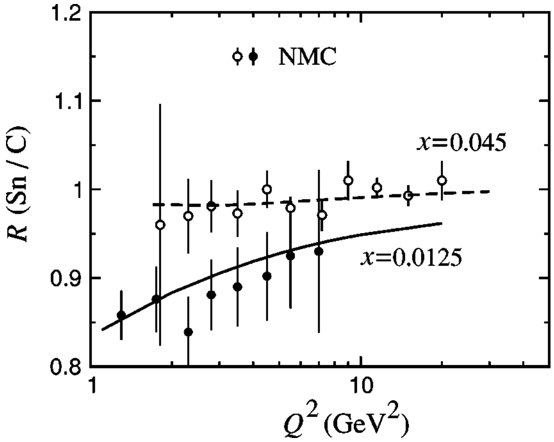

FIG. 1. Q^2 variation of the Sn/C structure function ratio in the model of Ref. [14] for $x=0.0125$ (solid) and $x=0.045$ (dashed). The data are from NMC [11], with statistical and systematic errors added in quadrature.

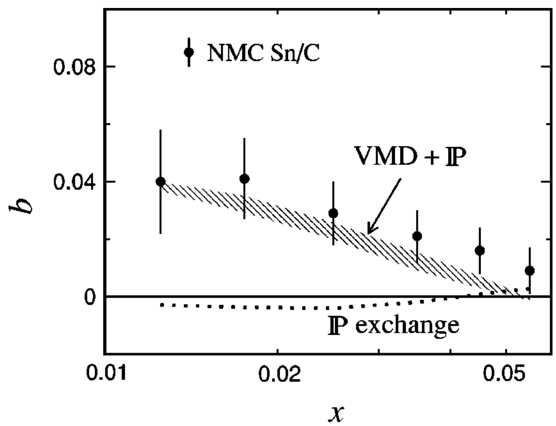

FIG. 2. Logarithmic slope b in Q^2 of the NMC Sn/C ratio as a function of x [11], compared with the nuclear shadowing model of Ref. [14]. The statistical and systematic errors are added in quadrature.

the VMD model dies off quite rapidly between $Q^2\sim 1$ and 10 GeV^2, so that for $Q^2 \gtrsim 10$ GeV^2 it is almost negligible—leaving only the diffractive partonic term, $\delta^{(\mathbb{P})}F_2^A$.

The accuracy of the model can be tested by looking for deviations from the logarithmic Q^2 dependence of shadowing at low and intermediate Q^2. Actually, a detailed analysis of the Q^2 dependence of the NMC data, as well as the lower-Q^2 Fermilab E665 data [26], was performed in Refs. [13,14] for various nuclei from $A=2$ to $A=208$ (viz., for D, Li, Be, C, Al, Ca, Fe, Sn, Xe, and Pb). Ratios of F_2^A/F_2^D were calculated [13,14] for a range of $x(10^{-5}\lesssim x \lesssim 0.1)$ and Q^2 ($0.03\lesssim Q^2 \lesssim 100$ GeV^2). Subsequent to these analyses, high precision data on the Q^2 dependence of Sn/C structure function ratios were published [11], which provided the first detailed evidence concerning the Q^2 dependence of nuclear shadowing.

In Fig. 1 we show the calculated ratio $R(\mathrm{Sn/C}) \equiv F_2^{\mathrm{Sn}}/F_2^{\mathrm{C}}$ as a function of Q^2 for $x=0.0125$ (solid curve) and $x=0.045$ (dashed), compared with the NMC data [11]. The overall agreement between the model and the data is clearly excellent. In particular, the observed Q^2 dependence of the ratios is certainly compatible with that indicated by the NMC data. At large Q^2 ($Q^2 \gtrsim 10$ GeV^2), the Q^2 dependence is very weak, as expected from a partonic, leading-twist mechanism [14]—see also Refs. [27–31]. In the smallest x bins, however, the Q^2 values reach down to $Q^2 \approx 1$ GeV^2. The data on the C/D and Ca/D ratios analyzed in Ref. [14] at even smaller $x(x \gtrsim 0.0003)$ extend down to $Q^2 \approx 0.05$ GeV^2. This region is clearly inaccessible to any model involving only a partonic mechanism, and it is essential to invoke a nonscaling mechanism here, such as vector meson dominance. One should also note that, even though the shadowing corrections may depend strongly on Q^2, because the nucleon structure function itself is rapidly varying at low Q^2, the Q^2 dependence of the ratio will not be as strong as in the absolute structure functions. In any case, the fact that the two-phase model [14] describes the NMC data over such a wide range of Q^2 gives one added confidence in extending this model to neutrino scattering [6].

To illustrate the Q^2 dependence of R over the full range of x covered in the NMC experiment, Arneodo *et al.* [11] parametrized the Sn/C ratio as $R(\mathrm{Sn/C}) = a + b \ln Q^2$, and extracted the logarithmic slopes $b = dR/d \ln Q^2$ as a function of x. As illustrated in Fig. 2, the NMC find that the slopes are positive and differ significantly from zero for $0.01 < x < 0.05$, indicating that the amount of shadowing decreases with increasing Q^2 [11]. The logarithmic slope b is found to decrease from ≈ 0.04 at the smallest x value to zero at $x \gtrsim 0.06$. The result of the model calculation [14] is perfectly consistent with the NMC data over the full range of x covered, as Fig. 2 demonstrates [see also Fig. 3(b) of Ref. [14]]. In particular, the $\mathbb{P}$-exchange mechanism alone, modified by applying a factor $Q^2/(Q^2+Q_0^2)$ [16,32] to ensure that $\delta^{(\mathbb{P})}F_2^A \to 0$ as $Q^2 \to 0$, is clearly insufficient [21] to describe the logarithmic slope in Q^2 at low x, whereas the addition of a VMD component does allow one to describe the data quite well (the shaded region indicates an estimate of the uncertainty in the model calculation).

In summary, the results of this analysis demonstrate that a combination of VMD at low Q^2 to describe the transition to the photoproduction region, with parton recombination, parametrized via $\mathbb{P}$-exchange, at high Q^2 allows one to accurately describe shadowing in electromagnetic nuclear structure functions over a large range of Q^2. As well as confirming that higher-twist effects are numerically important at intermediate $Q^2 \sim 1-4$ GeV^2, our findings also suggest that the two-phase model can serve as an excellent basis on which to reliably tackle the question of shadowing in neutrino reactions.

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