Longitudinal and Transverse Nuclear Shadowing

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Abstract: Nuclear shadowing arises from multiple scattering of the hadronic fluctuations ($|q\bar{q}\rangle, |q\bar{q}g...\rangle$) of the virtual photon in a nucleus. We predict different longitudinal and transverse shadowing and an A–dependence of $R \equiv \sigma_L/\sigma_T$ which can be up to a 50% effect. The possibility of detecting nuclear effects on R at HERA is discussed.

While there are very different ideas on the nature of the EMC effect at intermediate and large values of x, the situation seems to be less controversial at small x, the region of nuclear shadowing (NS). There is a general consensus that NS is due to the recombination of partons belonging to different nucleons. A concrete and quantitative realization of this old idea has been offered in [1] where NS is attributed to the multiple scattering of the hadronic fluctuations of the virtual photon in nuclei. One can thus speak of parton recombination in that the multiple scattering diagrams involve quarks and gluons which do not belong to a single nucleon. This approach leads rather naturally to the prediction of different shadowing effects in the longitudinal and transverse channels and consequently to an enhancement of $R \equiv \sigma_L/\sigma_T$ in nuclei [2]. In the following we shall sketch the derivation of this result and present some quantitative estimates. We shall also study the possibility of measuring nuclear effects on R at HERA.

In virtual-photon–nucleus scattering, using Glauber formalism, the nuclear cross section is given by

$$\sigma^{\gamma^* A} = A\,\sigma^{\gamma^* N} - 4\pi\,\frac{A-1}{A}\,\left.\frac{d\sigma^D}{dt}\right|_{t=0} \int d^2\vec{b}\; T^2(\vec{b}) + \dots\,, \tag{1}$$

where $d\sigma^D/dt$ is the $\gamma^* N$ diffraction dissociation cross section integrated over the mass M^2 of the excited hadronic states

$$\left.\frac{d\sigma^D}{dt}\right|_{t=0} = \int dM^2\;\left.\frac{d^2\sigma^D}{dt dM^2}\right|_{t=0}\;\mathcal{F}(k_L^2)\,. \tag{2}$$

The longitudinal form factor of the nucleus $\mathcal{F}(k_L^2)$ appearing in (2) suppresses heavy mass excitations corresponding to non negligible longitudinal momenta of the recoil proton, $k_L = (Q^2+M^2)/2\nu = x m_N\,(1+M^2/Q^2)$.

Eq. (1) establishes a link between the leading nuclear shadowing correction and the pomeron structure function which is proportional to $d\sigma^D/dt$. This allows relating the diffractive DIS

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currently under experimental study at HERA to the small-x nuclear phenomena which will hopefully be a future chapter of the HERA program.

In the Nikolaev–Zakharov picture of small–x DIS [3, 4] the double scattering term in (1) can be calculated on the basis of the Fock structure of the virtual photon interacting with the nucleus. At small x, the hadronic states into which the γ^* fluctuates ($|q\bar{q}\rangle, |q\bar{q}g\ldots\rangle$) have a very long lifetime $\sim 1/m_N x$ and their transverse size is frozen during the scattering process. Hence one can write the virtual photoabsorption cross sections for scattering off a nucleon $\sigma_{L,T}^{\gamma^* N}$ as (focusing for the moment on the $q\bar{q}$ Fock component)

$$\begin{aligned} \sigma_{L,T}^{\gamma^* N}(x,Q^2) &= \langle \sigma(\rho,x)\rangle_{L,T} \\ &\equiv \int_0^1 d\alpha \int d^2\vec{\rho}\; |\Psi_{L,T}(Q^2,\rho,\alpha)|^2\, \sigma(\rho,x)\,, \end{aligned} \tag{3}$$

where $\Psi_{L,T}$ are the $q\bar{q}$ wave functions of the virtual photon, ρ the transverse separation of the pair, α the momentum fraction carried by one of the components, and $\sigma(\rho,x)$ is the interaction cross section of the $q\bar{q}$ color dipole with the nucleon, which does not depend on the flavor and on the photon polarization. Glauber's expansion, written in terms of the dipole cross section, reads

$$\sigma_{L,T}^{\gamma^* A}(x,Q^2) = A\,\langle\sigma(\rho,x)\rangle_{L,T} - \frac{A-1}{4\,A}\,\langle\sigma(\rho,x)^2\rangle_{L,T}\int d^2\vec{b}\; T^2(\vec{b}) + \ldots\,, \tag{4}$$

where $\langle\sigma(\rho,x)\rangle_{L,T} \equiv \sigma_{L,T}^{\gamma^* N}(x,Q^2)$. By comparing eqs. (1) and (4) one identifies the contribution to $d\sigma^D/dt$ corresponding to the $q\bar{q}$ content of the photon (or of the pomeron, from another viewpoint) as

$$\left.\frac{d\sigma_{L,T}^{D,q\bar{q}}}{dt}\right|_{t=0} = \frac{\langle\sigma(\rho,x)^2\rangle_{L,T}}{16\,\pi}\,, \tag{5}$$

For small ρ, $\sigma(\rho,x)$ has the color transparency behavior $\sigma(\rho,x) \propto \rho^2$. Because of the structure of $\Psi_{L,T}(Q^2,\rho,\alpha)$ the dominant contribution to $\sigma_{L,T}^{\gamma^* N}$ comes from pairs of transverse size $\rho^2 \sim [m_q^2 + Q^2\,\alpha(1-\alpha)]^{-1}$. Symmetric pairs, with $\alpha \sim 1/2$ and $\rho^2 \sim 1/Q^2$, have $\sigma_{L,T} \sim (1/Q^2)\log(Q^2/m_q^2)$, *i.e.* scaling cross sections. Asymmetric pairs, with $\alpha \sim 0, 1$ and large size $\rho^2 \sim 1/m_q^2$, have a scaling transverse cross section $\sigma_T \sim 1/Q^2$, but a vanishing longitudinal cross section σ_L.

Because of the color transparency property of $\sigma(\rho,x)$, the second and higher terms in the series (4) contain powers of ρ^2. As a consequence, symmetric pairs with $\rho^2 \sim 1/Q^2$ give a $1/(Q^2)^2$, *i.e.* negligible, contribution to the double scattering term, whereas asymmetric pairs with $\rho^2 \sim 1/m_q^2$ lead to a scaling $1/Q^2$ screening. Since asymmetric pairs lead to a vanishing σ_L, we can conclude that shadowing in the longitudinal cross section is negligible at moderate and large values of Q^2, whereas it is significant and almost Q^2 independent in the transverse cross section. Thus, R is expected to be enhanced in nuclei for $Q^2 \gtrsim 5$ GeV^2.

So far we have considered only the lowest Fock state of γ^*, yielding the component $\propto M^2(M^2+Q^2)^{-3}$ of the mass spectrum. At large M^2 the triple pomeron component, related to the $q\bar{q}g$ Fock state of the photon, becomes dominant. Its mass spectrum is

$$\left.\frac{d\sigma_{L,T}^{D,3I\!P}}{dM^2\,dt}\right|_{t=0} = \sigma_{\rm tot}^{\gamma^* N}\, A_{3I\!P}\,\frac{M^4}{(Q^2+M^2)^3}\,. \tag{6}$$

Putting all terms together one ends up with

$$\sigma_{L,T}^{\gamma^* A}(x,Q^2) = A\,\sigma_{L,T}^{\gamma^* N}(x,Q^2) - \frac{A-1}{4\,A}\left\{\langle\sigma(\rho,x)^2\rangle_{L,T} + 16\pi\,\left.\frac{d\sigma_{DD}^{3I\!P}}{dt}\right|_{t=0}\right\}\int d^2\vec{b}\, T^2(\vec{b}) + \ldots\,, \tag{7}$$

A full calculation of the $3I\!\!P$ contribution has been performed [4], which has confirmed the behavior (6) both for the longitudinal and the transverse cross section and predicted a coupling $A_{3I\!\!P}$ substantially flavor and Q^2 independent for $Q^2 \gtrsim 2$ GeV^2.

Our estimate of $\Delta R \equiv R_A - R_N$ in [2] was based on eqs. (7) and (6), with $A_{3I\!\!P}$ taken phenomenologically from photoproduction data. Now, the $A_{3I\!\!P}$ value computed in [4] is somehow larger than the one used in [2]. This means that, since the triple pomeron contribution does not discriminate between longitudinal and transverse cross sections, the results for ΔR given in [2] slightly overestimate the nuclear effects on R. We correct them here by an educated guess, leaving a precise quantitative determination to a forthcoming paper.

Thus our prediction for $\Delta R \equiv R_A - R_N$ in the atomic mass range $A \simeq 30 - 80$ (say Cu–Pb), at $x = 10^{-3}$ and $Q^2 = 10$ GeV^2 is: $\Delta R \simeq 0.10 - 0.15$, that is a $30 - 50\%$ effect (with $R_N \simeq 0.30 - 0.35$). We found that at small $Q^2 \sim 1$ GeV^2 shadowing is similar in the longitudinal and transverse cross sections. We expect the largest nuclear effects at x around 10^{-3} and Q^2 larger than few GeV^2.

Let us address the problem of detecting nuclear effects on R at HERA. In order to extract R one has to use nucleon beams with at least two different energies. We consider the possibility of having two beams with nucleon energies $E_1 = 410$ GeV and $E_2 = 205$ GeV. The electron energy is 27.6 GeV.

We estimate now the statistical error on ΔR. By considering two targets A and B and the cross section ratios $\rho_1 \equiv \sigma_B^{(1)}/\sigma_A^{(1)}$ and $\rho_2 \equiv \sigma_B^{(2)}/\sigma_A^{(2)}$, corresponding to the two target energies, one easily finds the relation

$$\Delta R = (\rho - 1)\,(1 + \bar{R})\left[\frac{\rho\,(1 - z_2)}{1 + z_2 \bar{R}} - \frac{1 - z_1}{1 + z_1 \bar{R}}\right]^{-1}, \tag{8}$$

among $\Delta R \equiv R_A - R_B$, $\bar{R} \equiv (R_A + R_B)/2$, $z_{1,2} \equiv (1 - y_{1,2})/(1 - y_{1,2} + y_{1,2}^2/2)$, and the ratio of cross section ratios $\rho \equiv \rho_1/\rho_2$. It is clear from eq. (8) that in order to extract ΔR one needs $\bar{R}$, besides ρ. Since our purpose here is simply to evaluate the expected statistical error on ΔR, we use (8) as a constraint between $\bar{R}$ and ΔR [5]. In the following target B is assumed to be deuteron. We choose $x = 10^{-3}$, $Q^2 \simeq 20$ GeV^2, let $\bar{R}$ vary in a reasonable range around $0.3 - 0.4$, fix ρ so as to get a ΔR value around 0.10-0.15 (which is our estimate presented above), and calculate the error on ΔR. The statistical error on $\rho_{1,2}$, with a luminosity of 1 pb^{-1} per nucleon, is taken to be $\delta\rho_{1,2} = 0.0090$ (interpolating the values computed by Sloan [6]). We set $\rho_1 \simeq 0.80$ and, finally, assume a 30% error on $\bar{R}$. The result of our evaluation is shown in Fig. 1 where the solid line represents the central value of ΔR and the dashed and dotted lines mark the estimated statistical error with integrated luminosities of 1 pb^{-1} and 10 pb^{-1} per nucleon, respectively. The estimated statistical uncertainty on ΔR is thus $30 - 35\%$. Our conclusion is that the nuclear effects on R predicted by our model are visible at HERA and can be measured with a reasonable accuracy.

Finally we would like to comment on a different approach to parton recombination [7]. In the fusion model of [7] parton recombination is an initial state process and the shadowing of nuclear structure functions arises from the shadowing of the glue density, which is universal, not depending on the specific process or observable considered. Thus one would expect that all gluon–dominated physical quantities, such as F_2^A and F_L^A at small x, should behave similarly, at variance with our finding. However no quantitative results for R_A and ΔR have been provided so far for this class of models. It would be interesting to work out their predictions to see

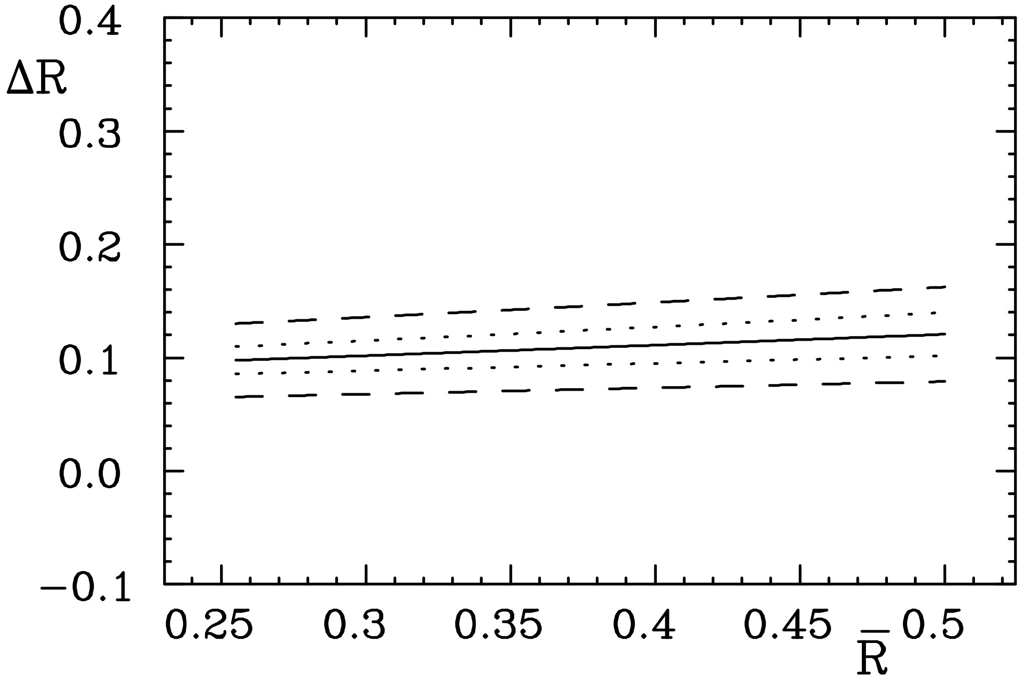

Figure 1: ΔR *vs.* $\bar{R}$ at $x = 10^{-3}$ and $Q^2 = 20$ GeV^2.

whether a possible HERA measurement of R_A and ΔR can also discriminate between different models of nuclear shadowing.

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