Binding effects and nuclear shadowing

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Abstract: The effects of nuclear binding on nuclear structure functions have so far been studied mainly at fixed target experiments, and there is currently much interest in obtaining a clearer understanding of this phenomenon. We use an existing dynamical model of nuclear structure functions, that gives good agreement with current data, to study this effect in a kinematical regime (low x, high Q^2) that can possibly be probed by an upgrade of HERA at DESY into a nuclear accelerator.

The ratio of the structure functions of bound and free nucleons is smaller than one at $x < 0.1$; this has been observed previously and is called nuclear shadowing [1]. Nuclear shadowing and its scaling proporties are generally regarded as the shadowing effect arising from gluon recombinations in the partonic model. A surprising fact of the HERA data is the rapid rise of the structure function F_2 of the proton as x decreases. The expected shadowing effect of gluon recombinations is not visible at least down to $x \sim 10^{-3}$ [2]. On the other hand, one of us (WZ) [3] has pointed out that the effect of shadowing due to gluon recombinations on a steep gluon distribution will be weakened by momentum conservation; in particular, gluon fusion can be neglected in the QCD nonlinear evolution equation in the small-x region where the gluon density rises like the Lipatov $x^{-1/2}$ behavior. Obviously, reconsideration of the partonic shadowing model is necessary. We have thus evolved a new approach to nuclear shadowing, which explains available data without needing Glauber rescattering [4]. On the other hand, there is a strong likelihood of HERA being upgraded to a nuclear accelerating machine [5]. We therefore apply our model and obtain predictions for the nuclear structure functions in the kinematical regime of the HERA machine.

The Model : We quickly review the model. We consider the DIS process in the Breit frame, where the exchanged virtual boson is point-like and the target consists of partons. The z-component of the momentum of the struck quark is flipped in the interaction. Hence, due to the uncertainty principle, a struck quark carrying a fraction x of the nucleon's momentum, P_N, during the interaction time $\tau_{\rm int} = 1/\nu$, will be off-shell and localized longitudinally to within a potentially large distance $\Delta z \sim 1/(2xP_N)$, which may exceed the average two-nucleon separation D_A for a small enough $x < x_0 = 1/m_N D_A$.

The struck sea quark with its parent will return to its initial position within $\tau_{\rm int}$ if the target is a free nucleon. However, in a bound nucleon target, it can interact with other nucleons in the nucleus and so loses its energy-momentum. Since it can be randomly distributed outside the target nucleon, and interacts incoherently with the rest of the nucleus, we regard this effect as an additive (second) binding effect rather than as a Glauber rescattering.

A simple way of estimating the second binding effect is to connect this new effect with the traditional binding effect, which influences the parton input distributions at the starting point, $Q^2 = \mu^2$, of the QCD evolution. At such low scales, we picture the nucleon as being composed of valence quarks, gluons, and mesonic sea quarks. For example, we identify the GRV (LO) parametrisations [6] as the input parton distributions of the free nucleon at $\mu^2 = 0.23$ GeV^2.

We consider that the attractive potential describing the nuclear force arises from the exchange of scalar mesons. Hence the energy required for binding is taken away solely from the mesonic component of the nucleon, and not from its other components. We identify this with the sea quarks (and antiquarks) in the nucleon. Therefore, we assume that the nuclear binding effect only reduces the sea distributions of the nucleon at $Q^2 = \mu^2$.

For a binding energy, b, per nucleon, this corresponds to the reduction of the bound nucleon sea densities from the free-nucleon value, $S_N(x, \mu^2)$, given by GRV at $Q^2 = \mu^2$ to

$$\begin{aligned} S_A(x, \mu^2) &= K(A) S_N(x, \mu^2) \\ &= \left(1 - \frac{2b}{M_N \langle S_N(\mu^2) \rangle_2}\right) S_N(x, \mu^2) \ . \end{aligned} \tag{1}$$

Here $\langle S_N \rangle_2$ is the momentum fraction (second moment) of the sea quarks and we assume that the decrease in number of sea quarks due to the binding effect is proportional to their density.

We assume that the energy loss of sea quarks, $U_s(Q^2)$, due to the second binding effect is also proportional to the density,

$$U_s(Q^2) = \beta M_N \int_0^{x_0} x S_A(x, Q^2) \simeq \beta M_N \langle S_A(Q^2) \rangle_2 \ , \tag{2}$$

and the strength of this interaction is similar to eq. (1), viz.,

$$\beta = \frac{U_s(Q^2)}{M_N \langle S_A(Q^2) \rangle_2} = \frac{U(\mu^2)}{M_N \langle S_N(\mu^2) \rangle_2} \ , \tag{3}$$

$U(\mu^2) = a_{\rm vol}/6$ being the binding energy between each pair of nucleons. In consequence, we have, due to the second binding effect, a depletion of the sea quarks, given by

$$S_A(x, Q^2) - S'_A(x, Q^2) = \beta S_A(x, Q^2) \ . \tag{4}$$

Combining the above mentioned two kinds of binding effects and the swelling effect on a bound nucleon, which was discussed in ref. [7], we are able to explain recent data on the EMC effect in a broad kinematical region using only a few fundamental nuclear parameters [4].

Predictions for HERA : Our model predicts correctly the A-, Q^2 and x-dependences of the nuclear structure functions (and not only the ratio of cross sections) measured by the NMC in the ranges of $x < 0.8$, $Q^2 > 0.5$ GeV^2. However, being a fixed target experiment, the available Q^2 range is limited. It would therefore be interesting, as well as instructive, to obtain more results and predictions in the small-x region, and in a larger Q^2 range.

We have done this for the case of a few typical nuclei, the results for which are shown in Fig. 1. We see that the small-x shadowing is weakly dependent on Q^2 and is dominated by the second binding effect. Due to this, there is hardly any x-dependence, as saturation has already set in by $x \sim 10^{-2}$. However, the magnitude of the shadowing is large for heavier nuclei.

We therefore conclude that it would be definitely worthwhile to make the effort to study such processes at HERA in an attempt to understand better the nature of the binding of nucleons in nuclei.

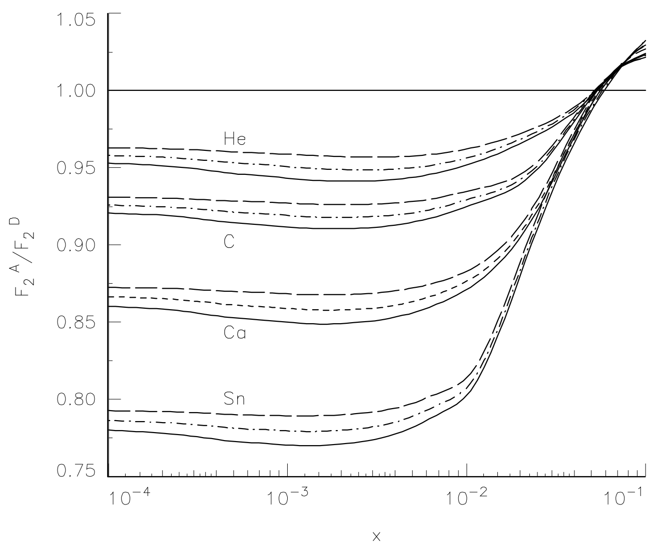

Figure 1: *The structure function ratios as functions of x and Q^2 for He/D, C/D, Ca/D, and Sn/D. The full, broken, and long-dashed curves correspond to $Q^2 = 4, 30$, and 100 GeV^2 respectively.*

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