NUCLEAR EFFECTS IN DEEP INELASTIC LEPTON SCATTERING*

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We discuss nuclear effects in deep inelastic lepton scattering. At small values of the Bjorken variable $x < 0.1$ shadowing effects are due to the coherent interaction of hadronic Fock components of the exchanged, virtual photon. It turns out that in the kinematic regime of current experiments the contribution of the vector mesons are of major importance. At moderate and large $x > 0.2$ nuclear effects are caused by binding and Fermi motion, but also by off-shell modifications of bound nucleon structure functions.

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1. Introduction

Deep inelastic lepton scattering from nuclei is a powerful tool to investigate the quark-gluon structure of nucleons in a nuclear environment. The cross-section of this process is studied as a function of the Bjorken variable $x = Q^2/2M\nu$ and the squared four-momentum transfer $Q^2 = -q^2$, where M is the nucleon mass and ν is the photon energy in the laboratory frame. Accurate experimental data [1–6] are now available for a number of nuclear targets over a wide kinematical range, $5 \cdot 10^{-5} < x < 0.8$ and $0.03\,\mathrm{GeV}^2 < Q^2 < 200\,\mathrm{GeV}^2$. The data show nontrivial nuclear effects over the whole range of Bjorken x. At $x < 0.1$ one observes shadowing, *i.e.* a systematic reduction of the nuclear structure function F_2^A with respect to A times the free nucleon structure function F_2^N. A small enhancement of the

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ratio $R = F_2^A/AF_2^N$ is seen at $x \approx 0.2$ and a pronounced dip occurs in that ratio at $x \sim 0.5$. Finally for $x > 0.7$ a large enhancement of R is observed.

Numerous models have been proposed to explain these effects (for recent reviews see *e.g.* Refs [7]). So far, most theoretical models for nuclear deep inelastic scattering give separate descriptions of the regions of small $x < 0.1$ and large $x > 0.2$. The physical reason for such a division becomes apparent in the space-time analysis of the deep inelastic scattering process. In the laboratory frame the interaction of the virtual photon with the target can proceed in two possible ways:

(I) the photon is absorbed by a quark or antiquark in the target which picks up the large energy and momentum transfer;

(II) the photon converts into a quark-antiquark pair which subsequently interacts with the target.

An analysis of the contributions (I) and (II) reveals that the second mechanism dominates at small $x \ll 0.1$ (see *e.g.* the discussions in [8]). For $x > 0.1$ both processes (I) and (II) contribute.

In order to understand the implications of this for nuclear targets let us consider characteristic space-time scales. Mechanism (I) has a characteristic scale which is determined by the size of the nucleon and does not depend on x. For mechanism (II) the propagation length λ of the $q\bar{q}$ (or hadronic) fluctuations of the photon in the laboratory frame is $\lambda \sim (2Mx)^{-1}$. For $x < 0.05$ this propagation length becomes larger than the average nucleon-nucleon distance in nuclei. As a consequence deep inelastic scattering from nuclear targets at small x involves the coherent interaction of the pair with several nucleons in the nucleus. This leads to nuclear shadowing.

At moderate and large $x > 0.2$, effects resulting from coherent multiple scattering in the nucleus are not important since the space-time scales of both mechanisms (I) and (II) are of the order of the nucleon size. In this region of x the virtual photon interacts incoherently with bound nucleons. Model descriptions of nuclear structure functions in the $x > 0.2$ region usually start out from the impulse approximation in which final state interactions between the scattered nucleon and the nuclear remnant are neglected [7]. We discuss the limitations of the standard convolution model and point out that at $x > 0.2$ nuclear effects are due to nuclear binding and Fermi motion, but also off-shell modifications of bound nucleon structure functions can be important.

2. Deep inelastic scattering at small x

Before discussing nuclear effects in deep inelastic scattering at $x < 0.1$, we will model the free nucleon structure function F_2^N at small x. We focus on the kinematic regime of the recent NMC [1, 2] and E665 [3, 4] experiments where shadowing effects have been measured. In this kinematic region the nucleon structure function F_2^N depends only weakly on x for $10^{-3} < x < 0.1$, as observed by the NMC collaboration [9]. Measurements of nuclear structure functions in the region where F_2^N exhibits a strong rise with decreasing $x < 10^{-4}$, as found recently at HERA (see *e.g.* [10]), are currently not possible.

2.1. The free nucleon structure function F_2^N at $x < 0.1$

The free nucleon structure function $F_2^N(x, Q^2)$, defined as the average of the proton and the neutron structure function, can be written in terms of the virtual photon-nucleon cross section $\sigma_{\gamma^* N}$. At $x < 0.1$ we have:

$$F_2^N(x, Q^2) = \frac{Q^2}{4\pi^2 \alpha_{\text{em}}} \sigma_{\gamma^* N}. \tag{1}$$

We will consider only contributions from transversely polarized photons, as they constitute the dominant part of the cross section.

As discussed above, at small x the virtual photon interacts with the nucleon by first converting into a $q\bar{q}$ pair which then propagates, forming a hadronic intermediate state that interacts strongly with the nucleon. This is expressed in the following spectral ansatz for the structure function valid at $x < 0.1$ (see *e.g.* [11, 12, 13, 14]):

$$F_2^N(x, Q^2) = \frac{Q^2}{\pi} \int_{4m_\pi^2}^{\infty} d\mu^2 \int_0^1 d\alpha \frac{\mu^2\, \Pi(\mu^2)}{(\mu^2 + Q^2)^2}\, \sigma_{hN}(\mu^2, \alpha). \tag{2}$$

Here $\Pi(\mu^2)$ is the spectrum of hadronic fluctuations with mass μ which is related to the measured cross section for $e^+e^- \to$ hadrons by:

$$\Pi(s) = \frac{1}{12\pi^2} \frac{\sigma_{e^+e^- \to \text{hadrons}}(s)}{\sigma_{e^+e^- \to \mu^+\mu^-}(s)}. \tag{3}$$

The cross section σ_{hN} for the scattering of a hadronic fluctuation from the nucleon can depend on the invariant mass μ of the hadronic fluctuation, but also on α, the fraction of the photon light-cone momentum carried by the quark. The factor $(\mu^2+Q^2)^{-2}$ in Eq. (2) comes from the propagators of the hadronic intermediate states.

The structure function $F_2^N(x,Q^2)$ in Eq. (2) is dominated by contributions from intermediate states with an invariant mass $\mu^2 \sim Q^2$. As a consequence, for small momentum transfer, $Q^2 < 1\mathrm{GeV}^2$, the low mass vector mesons ρ, ω and ϕ are of major importance. Their interaction cross sections can be determined to some extent in real and virtual photoproduction experiments as given in [14]. The dominance of the vector meson contributions at small values of x and Q^2 leads to the scale breaking behavior $F_2^N(x,Q^2) \sim Q^2$ for $Q^2 \to 0$.

For larger values of the momentum transfer, *i.e.* $Q^2 > m_\phi^2 \approx 1\mathrm{GeV}^2$, the nucleon structure function F_2^N is governed by the interaction of quark-antiquark pairs with mass $\mu^2 \sim Q^2 > 1\mathrm{GeV}^2$. Apart from the narrow charmonium and upsilon resonances, these quark pairs form the so-called $q\bar{q}$ continuum. In the annihilation of e^+e^- into hadrons they are responsible for the approximately constant behavior of the cross section ratio at large timelike momenta, $\sigma_{e^+e^-\to\mathrm{hadrons}}/\sigma_{e^+e^-\to\mu^+\mu^-} \approx 3\sum_f e_f^2$, where we sum over the fractional charges e_f of all quark flavors which are energetically accessible.

To calculate the contribution of the continuum quark-antiquark fluctuations to the nucleon structure function we need to know their effective interaction cross section. Since the $q\bar{q}$ fluctuations of the photon are color singlets, we assume their cross sections to scale with their transverse size ρ (*i.e.* their size in a plane perpendicular to their momentum) as $\sigma \sim \rho^2$. At small transverse sizes ρ^2 can be calculated perturbatively [15], while for sizes of the order of the confinement scale, strong, non-perturbative interactions will lead to a saturation of ρ. Having this in mind, we choose for the effective cross section of continuum quark-antiquark pairs:

$$\sigma_{hN}(\mu^2,\alpha) = K\cdot\rho^2 = K\cdot\min\left\{\begin{array}{l} R_c^2 \\ \dfrac{1}{\alpha(1-\alpha)}\,\dfrac{4\mu^2}{(\mu^2+Q^2)^2}, \end{array}\right. \tag{4}$$

with a constant K to be determined. Here we have introduced a maximum radius R_c which should be in the range of the confinement scale.

While the vector meson part vanishes as $1/Q^2$ for large Q^2, the $q\bar{q}$ continuum contribution to the structure function displays logarithmic scaling behavior:

$$F_2^N(x,Q^2) \sim \ln\left(R_c^2Q^2\right) \quad \text{for} \quad Q^2 \gg 1\mathrm{GeV}^2. \tag{5}$$

To compare our result for the free nucleon structure function F_2^N with recent data from the New Muon Collaboration [9] we include in Eq. (2) all vector mesons ρ, ω, ϕ, J/ψ and ψ'. (Their masses, coupling constants and cross sections are summarized in [14].) The constant K in Eq. (4) is fixed at $K = 1.7$ together with $R_c = 1.3$ fm. This corresponds to a maximum value of about 29 mb for the effective cross section of a $q\bar{q}$ pair interacting with a nucleon. From Fig. 1 one can see that our model reproduces the measured

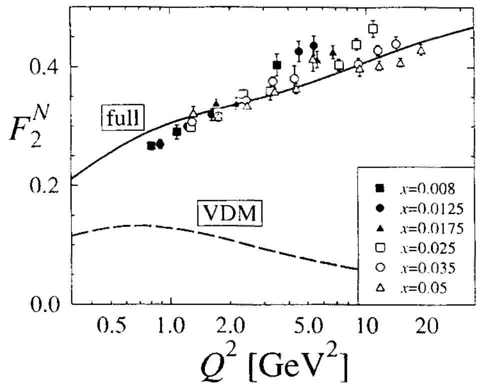

Fig.1. Nucleon structure function for small x plotted against Q^2. The solid line is the full result of our calculation in [14]. The contribution of the vector mesons is indicated by the dashed line. We compare to NMC data from ref.[9].

nucleon structure function at small x quite well. We want to emphasize again the importance of the vector mesons at small values of Q^2. In detail we find that at $Q^2 = 1\text{GeV}^2$ almost half of F_2^N at $x = 0.01$ is due to the vector mesons. At $Q^2 = 10\text{GeV}^2$ their contribution is still around 15%.

2.2. Deep inelastic scattering from nuclei at $x < 0.1$

Just like the scattering from free nucleons, scattering from nuclear targets at small values of x proceeds via the interaction of hadronic components present in the spectral function of the exchanged photon. For $x < 0.1$ the nuclear structure function F_2^A can therefore be written in a way analogous to F_2^N in Eq. (2):

$$F_2^A(x, Q^2) = \frac{Q^2}{\pi} \int_{4m_\pi^2}^{\infty} d\mu^2 \int_0^1 d\alpha \, \frac{\mu^2 \Pi(\mu^2)}{(\mu^2 + Q^2)^2} \, \sigma_{hA}(\mu^2, \alpha). \tag{6}$$

We have just replaced the hadron-nucleon cross sections σ_{hN} in Eq. (2) by the corresponding hadron-nucleus cross sections σ_{hA}.

As mentioned in the introduction, at $x < 0.05$ the coherence length $\lambda = 2\nu/(Q^2+\mu^2)$ of the interacting hadronic fluctuation exceeds the average inter-nucleon distance in nuclei. Consequently the intermediate hadronic system can scatter coherently from several nucleons in the target. Interference between the multiple scattering amplitudes causes a reduction of the hadron-nucleus cross sections compared to the naïve result of just A times the respective hadron-nucleon cross sections and thus leads to shadowing.

In the kinematic regime of the recent NMC and E665 data [1, 3] we may in good approximation consider for intermediate and heavy nuclei only elastic rescattering processes of the incoming hadronic state h from the nucleons inside the target. Contributions of inelastically produced states to multiple scattering were investigated by Murthy *et al.* [16] and Nikolaev [17] for high energy hadron-nucleus scattering processes. They found such contributions to be small, though rising logarithmically with the projectile energy ν. For example at $\nu \sim 100\text{GeV}$ inelastic terms account typically for $\sim 5\%$ of the total hadron-nucleus cross sections under consideration.

For a Gaussian nuclear density

$$\rho(\vec{r}) = \frac{1}{\pi^{3/2}a^3} \exp\left(-\frac{\vec{r}^{\,2}}{a^2 A^{2/3}}\right) \quad \text{with} \langle r^2 \rangle^{1/2} = \sqrt{\frac{3}{2}}\, aA^{1/3}$$

one then obtains the hadron-nucleus cross section σ_{hA} from the Glauber-Gribov multiple scattering series [18, 11] as:

$$\sigma_{hA} \approx A\sigma_{hN} \left[1 - A^{1/3} \frac{\sigma_{hN}}{8\pi a^2} \frac{A-1}{A} \exp\left(-\frac{a^2 A^{2/3}}{2\lambda^2}\right) + \dots\right]. \quad (7)$$

We observe that the double scattering contribution adds to the single scattering term a negative correction, the magnitude of which grows as $A^{1/3}$. Furthermore we notice that the shadowing correction decreases rapidly if the coherence length of the scatterer becomes small, $\lambda < \langle r^2 \rangle^{1/2}$.

Being able to obtain the total hadron-nucleus cross sections σ_{hA} from the respective hadron-nucleon cross sections σ_{hN}, the nuclear structure function as given in Eq. (6) can be calculated. Our numerical results in Ref. [14] were obtained with two 'extreme' parameterizations for the used nuclear matter densities: a Gaussian shape for small A and a square well shape for heavier nuclei. In both cases we fitted the mean square radii of these density distributions to empirical nuclear radii. It should be noted, that in earlier calculations [13] we have used realistic densities and included two-nucleon correlations, but we found the resulting corrections in both cases to be systematically very small. We will now present results from [14] for the shadowing ratio:

$$R(x, Q^2) = \frac{F_2^A(x, Q^2)}{A\, F_2^N(x, Q^2)}. \quad (8)$$

Figure 2 shows the calculated ratios for various nuclei, together with experimental results obtained by the NMC at CERN [1, 2] and the E665 collaboration at FNAL [3, 4]. We see that for $x < 0.1$ the ratio (8) is generally below one, *i.e.* shadowing occurs and it is well described within our model.

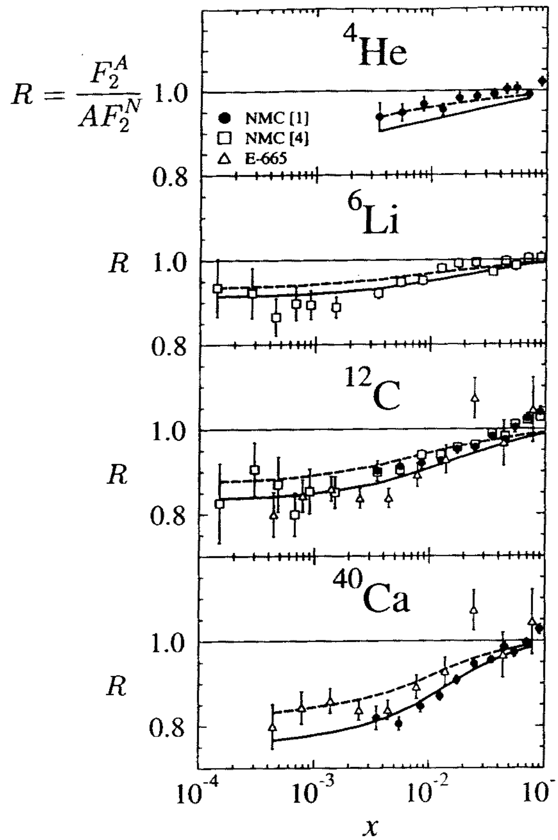

Fig.2. Our results for shadowing in He, Li, C, and Ca from [14] compared to available experimental data [1, 2, 4]. The dashed curves show the shadowing caused by the vector mesons ρ, ω and ϕ only.

It should be noted, that the shadowing ratio (8) is not just a function of x but also depends (weakly) on Q^2. The value of Q^2 basically selects that part of the hadron mass spectrum $\mu^2 \sim Q^2$ which dominates the interaction, and hence determines which cross sections σ_{hN} contribute significantly to the multiple scattering series. It should be stressed, that σ_{hN} depends not only on the mass μ of the $q\bar{q}$ pair, but also on the distribution of momenta within that pair. While the averaged interaction cross sections decrease as $\log(\mu^2)/\mu^2$ with increasing mass, pairs which are asymmetric in the $q\bar{q}$ phase space interact with large cross sections, even for large μ, and therefore produce strong shadowing. This is the reason for the very weak overall Q^2-dependence of the shadowing effect.

The relevant experiments all operate on fixed targets within a limited range of muon energies, hence Q^2 is not an independent parameter but depends on the x-range considered. We have taken this dependence into account by inserting into our calculation the mean Q^2 values reported for the different x-bins of the experiments. With decreasing x the accessible values for Q^2 also become small (*e.g.* at $x = 0.005$, $Q^2 \sim 1\text{GeV}^2$ for the NMC experiment from Ref. [1]). Therefore the contributions of the low mass vector mesons ρ, ω and ϕ dominate the observed shadowing at $x < 0.01$ as indicated in Fig. 2.

The NMC [1, 2] has analyzed the Q^2-dependence of shadowing by performing linear fits $R(x, Q^2) \approx a + b \ln Q^2$ to the data for every x-bin. Fig. 3 shows the slopes b obtained in that way in comparison with our calculations. We see that the NMC data are compatible with basically no Q^2-dependence. Our calculations give a very small positive slope, *i.e.* a slow decrease in shadowing with increasing Q^2 which is within the range of the NMC data. New high statistic NMC data [19] on the Q^2-dependence of the structure function ratio Sn/C clearly reveal shadowing as a leading twist effect — in agreement with our description in [14].

Both the E665 data on Xenon [4] and the recent NMC data for Carbon and Lithium [2] extend to rather small values of x ($x < 10^{-3}$). In this region a saturation of the shadowing effect becomes apparent, with the ratio eventually approaching the 'photon point', *i.e.* the value observed in the scattering of real photons from nuclei. As outlined in Ref. [14] these data are taken at very small Q^2 and therefore exhibit rather a "saturation" at low Q^2 than a "saturation" in x.

A more detailed discussion of the A-dependence of the shadowing effect, including deuterium as a target is given in Ref. [14].

3. Deep inelastic scattering from nuclei at moderate and large $x > 0.2$

In the region of moderate and large $x > 0.2$ nuclear structure functions are commonly described within the impulse approximation. Here deep inelastic scattering from a nucleus is considered as a two-step process, in terms of the virtual photon–nucleon interaction, parameterized by the truncated nucleon tensor $\widehat{W}_{\mu\nu}(p, q)$, and the nucleon–nucleus scattering

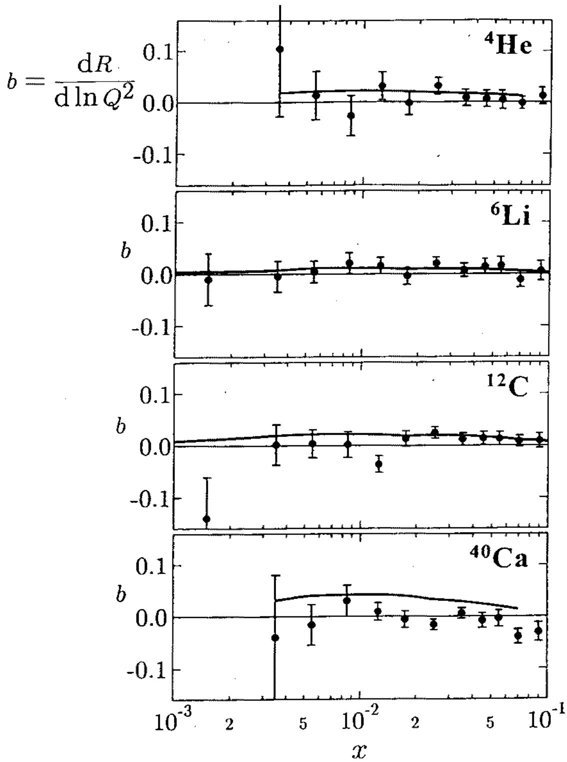

Fig.3. The slope $b = dR/d\ln Q^2$ indicating the Q^2-dependence of the shadowing ratio for He, Li, C, and Ca extracted by the NMC [1, 2] for various x-bins together with our results from [14].

amplitude $\widehat{A}(p, P)$. The nuclear hadronic tensor can then be written as:

$$M_A\, W^A_{\mu\nu}(P, q) = \int \frac{d^4p}{(2\pi)^4 i} \mathrm{Tr}\left[\widehat{A}(p, P)\ \ \widehat{W}_{\mu\nu}(p, q)\right], \tag{9}$$

where P, p and q are the nucleus, off-shell nucleon and photon momenta respectively, and M_A is the mass of the nuclear target.

The truncated nucleon tensor $\widehat{W}_{\mu\nu}$ is invariant under parity, charge conjugation and time reversal. Furthermore it must be hermitian and gauge invariant [20, 21]. As a consequence one finds that the bound off-shell nucleon is described by *six* structure functions which depend on Q^2 and x but also on p^2, the squared four momentum of the bound nucleon [20, 22]. Deep inelastic scattering from free nucleons determines only two structure functions at the on-shell point $p^2 = M^2$. Consequently in a relativistic description of deep inelastic scattering from nuclei the conventionally used convolution of the momentum distribution of nucleons in the nucleus and on-shell nucleon structure functions (see *e.g.* references in [7]) fails, as shown in [20, 22].

However as pointed out in Ref. [22] one may obtain for nuclear structure functions a factorization of nuclear and nucleon parts, if the nucleons in the nucleus are treated non-relativistically. Neglecting anti-nucleon degrees of freedom and terms of the order $|\vec{p}^3|/M^3$ and higher, yields:

$$F_2^A(x) = \int_x dy \int dp^2\, D_{N/A}(y,p^2) F_2^N(x/y;p^2). \tag{10}$$

It should be noted, that this *two*-dimensional convolution explicitly takes into account off-shell modifications of the bound nucleon structure function. The nucleon light-cone distribution $D_{N/A}$ is determined by the nucleon spectral function $S(p)$:

$$D_{N/A}(y,p^2) = \int \frac{d^4p'}{(2\pi)^4} S(p') \left(1+\frac{p'_3}{M}\right) \delta\left(y-\frac{p'_+}{M}\right) \delta(p^2-p'^2). \tag{11}$$

Let us examine Eq. (10) in more detail. The nucleon distribution (11) is strongly peaked around $p^2 = M^2$ and $y = 1$, with a characteristic width $\Delta y \sim p_F/M$, where p_F is the nucleon Fermi-momentum. Expanding the bound nucleon structure function in Eq. (10) in a Taylor series around these points and integrating term by term, one obtains the following expression for the nuclear structure function per nucleon [22]:

$$\begin{aligned}\frac{F_2^A(x)}{A} \simeq{}& F_2^N(x) - \frac{\langle\varepsilon\rangle}{M}\, xF_2^{N\prime}(x) + \frac{\langle T\rangle}{3M}\, x^2 F_2^{N\prime\prime}(x) \\ &+2\,\frac{\langle\varepsilon\rangle - \langle T\rangle}{M} \left(p^2 \frac{\partial F_2^N(x;p^2)}{\partial p^2}\right)_{p^2=M^2}.\end{aligned} \tag{12}$$

Here $F_2^{N\prime}(x)$ and $F_2^{N\prime\prime}(x)$ are derivatives of the structure function with respect to x, and $\langle\varepsilon\rangle$ and $\langle T\rangle$ are the mean separation and kinetic energies of the bound nucleon:

$$\langle\varepsilon\rangle = \frac{1}{A}\int \frac{d^4p}{(2\pi)^4} S(p)\, \varepsilon, \tag{13}$$

$$\langle T\rangle = \frac{1}{A}\int \frac{d^4p}{(2\pi)^4} S(p)\, \frac{\mathbf{p}^2}{2M}. \tag{14}$$

Corrections to Eq. (12) are of higher order in $\langle\varepsilon\rangle/M$ and $\langle T\rangle/M$. One should note that Eq. (12) can safely be used for $1 - x > p_F/M \sim 0.3$. In this region the condition $x/y \le 1$ gives practically no restrictions on the integration over the nucleon momentum p in Eqs (13,14). The second term

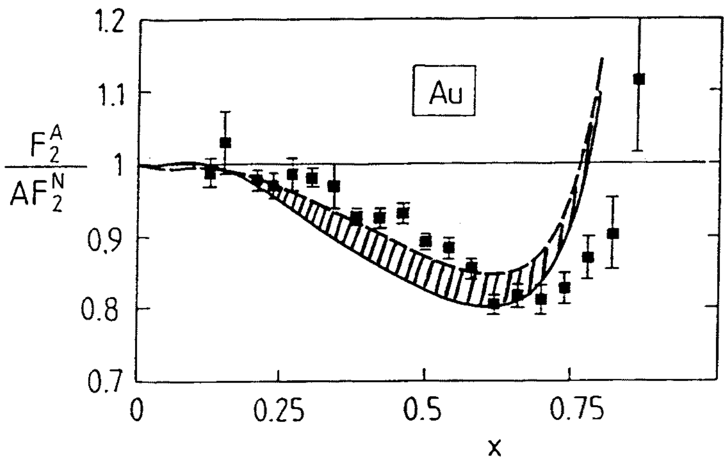

Fig.4. The ratio F_2^A/AF_2^N of the nuclear and nucleon structure function calculated in ref.[22] using Eq. (12) with $\langle\varepsilon\rangle = -50\,\mathrm{MeV}$ and $\langle T\rangle = 20\,\mathrm{MeV}$. The shaded area shows the sensitivity of nuclear effects to off-shell modifications of the bound nucleon structure function. The experimental data for ^{197}Au are taken from [6].

on the r.h.s. of Eq. (12) leads at moderate values of $0.3 < x < 0.7$ to a depletion of the nuclear structure function compared to the free nucleon one, due to the binding of the nucleons inside the nucleus. The third term accounts for the Fermi-motion of the bound nucleons and yields a strong rise of the structure function ratio F_2^A/AF_2^N at large $x > 0.8$. The forth term in (12) is new and reflects the leading contribution from the p^2-dependence of the bound nucleon structure function.

In Fig. 4 we show the sensitivity of F_2^A to nuclear effects caused by off-shell modifications of the bound nucleon structure function. These are sketched within a spectator model leading to an 1% swelling of nucleons inside nuclei (for details see Ref. [22]). For the mean separation and mean kinetic energies we choose $\langle\varepsilon\rangle/M = -50\,\mathrm{MeV}$ and $\langle T\rangle = 20\,\mathrm{MeV}$. Although we find a qualitative agreement with experimental data for the structure function ratio F_2^A/AF_2^N, off-shell modifications of the bound nucleon structure function lead to a $\sim (5-8)\%$ effect at $x \sim 0.5 - 0.7$.

4. Summary

We discussed nuclear effects in deep inelastic lepton scattering. At small values of the Bjorken variable $x < 0.1$ coherent multiple scattering of hadronic Fock components of the exchanged virtual photon is responsible for the observed shadowing effect. In the kinematic domain of current experiments from the NMC and E665 collaboration we found, that the vector mesons cause most of the observed shadowing effect. On the other hand, contributions from continuum $q\bar{q}$ pairs guarantee a week Q^2-dependence of shadowing.

At moderate and large $x > 0.2$ incoherent scattering from bound nucleons inside the nuclear target is important. Starting from the impulse approximation it has been found that popular convolution models are in variance with a relativistic description of deep inelastic lepton-nucleus scattering. Treating the bound nucleons in a non-relativistic manner leads to a *two*-dimensional convolution which includes off-shell modifications of the structure functions of bound nucleons. Nuclear effects at $x > 0.2$ are then due to binding and Fermi-motion, but also off-shell effects.

For a more quantitative understanding of the structure of bound nucleons semi-inclusive experiments are needed, *e.g.* tagged structure function measurements as planned at HERMES [23].

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