PARTIAL DECONFINEMENT OF NUCLEONS INSIDE THE NUCLEAR MATTER AS SEEN BY DEEP INELASTIC ELECTRON–NUCLEUS SCATTERING*

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We argue that results on deep inelastic e–A scattering show partial deconfinement of nucleons inside the nuclear matter enhancing therefore the role played by the partonic degrees of freedom. In particular, we show that magnitude of the nuclear Fermi motion is sensitive to the residual interactions between partons, influencing both the nucleon structure function and the value of nucleon mass in the nuclear medium.

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1. Introduction

Nuclear medium EMC effect is the structure in the ratio $R(x)$ of nuclear to nucleon structure function, which is clearly seen (Fig. 1) in deep inelastic scattering e–A data [1] in the the region $0.1 < x < 1$. It is usually described by a two step mechanism accounting for the fact that nuclei are composed out of nucleons, which are composed out of partons. It can be summarized by writing that [2]

$$\frac{1}{x_A}F_2^A(x_A) = A\int\int dy_A \frac{dx}{x}\delta(x_A - y_A x)\rho^A(y_A)F_2^N(x)\,. \tag{1}$$

Here $F_2^A(x_A)$ denotes the nuclear structure function (SF), which is at first composed from nucleons distributed according to nuclear spectral function, $\rho^A(y_A)$, and which, in turn, are described in the partonic language by nucleonic SF $F_2^N(x)$.

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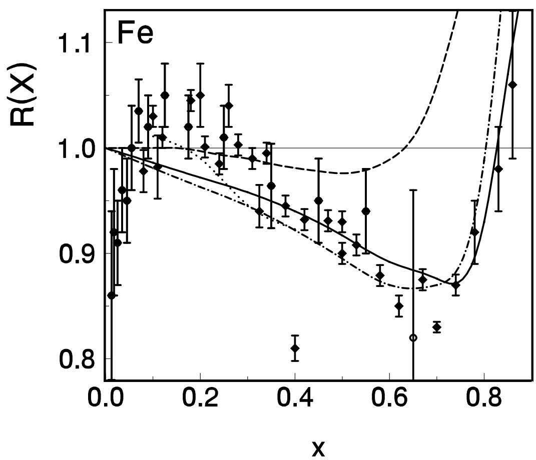

Fig. 1. Results for $R(x) = F_2^A(x)/F_2^D(x)$ for ^{56}Fe. Data are from [1]. See text for explanations.

The meaning of variables is the usual one: $x_A = p_q^+/P_A^+$ is the ratio of the quark and the nucleus longitudinal momenta (the Bjorken variable for the nucleus), $y_A = p^+/P_A^+$ is the ratio of the nucleon and nuclear longitudinal momenta, p^+ and P_A^+ ,and x is the ratio of the quark and nucleon longitudinal momenta (the Bjorken variable for the nucleon). The function $\rho^A(y_A)$ is the probability that a nucleon has longitudinal momentum fraction y_A. Notice that momenta ratios x and y which occur here are defined on different energy scales: nucleonic and nuclear, respectively.

The fact that F_2^A is not a simple product of F_2^N's means that either division between the two levels mentioned above is not correct or that nucleons inside the nuclear matter differ substantially from free ones (or both).

2. Non-nucleonic degrees of freedom in nuclei

In the first case it means that some additional level of complexity, not accounted for by the ρ^A, exists. It is usually attributed to additional mesonic degrees of freedom present in nuclei [3] and it can be described by changing accordingly the nuclear structure function (*i.e.* by adding nuclear pions or multi-quark clusters [4]). Two possible scenarios for the origin of nuclear binding: **A** and **B** are presented in Fig. 2.

Scenario **B** present classical Yukawa picture with intermediate pions [5] whereas scenario **A** makes the gluon field responsible for the nuclear interaction, specially for short relative distances where nucleons can overlap (with predominantly colorless 2 gluon exchanges). Both scenarios should describe the sea q–$\bar{q}$ content of the nucleons (the other Fock space components [6]).

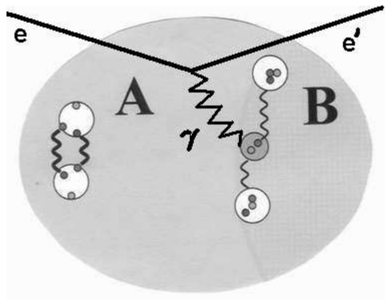

Fig. 2. Two different mechanisms **A** and **B** of nucleonic interaction inside nucleus and possible contribution to deep inelastic electron scattering from nuclear mesons (*i.e.*, mesons exchanged between nucleons.)

However, as was shown in [7], scenario **B** is excluded for distances smaller then $\sim$ 0.6fm by data on lepton-pair production on nuclei (they exclude also another scenario with multi-clusters description of Drell–Yan process in nuclei). Only small admixture, up to $(p_\pi^+)_{\rm av}/M_A \simeq 1\%$, of total average momentum carried by pion in the nucleus, is possible. This fact is in agreement with another medium energy experiment [8] measuring 500 MeV polarized proton scattering from nuclei. In this experiment proton is scattered from a nuclear target and becomes a neutron. No change in the measured spin dependence was found with respect to nucleon–nucleon scattering and it means that there is no pion excess (assuming the pion absorption and emission mechanism for this charge exchange reaction). The experiment was sensitive to the same range of pion momenta as that probed in [7] with the lepton Drell–Yan production. We have therefore to find medium modification mechanism in order to describe the strong depletion for $x > 0.3$, observed in the deep inelastic scattering data, *cf.* Fig. 1 for iron.

3. Nucleon modifications in the medium

Our proposal is to change of nucleon structure function in the medium due to the possible appearance of partial deconfinement of nucleons inside the nucleus[1]. In what follows we shall pursue this second conjecture. Our model, which contains essentially no free parameters, continues essentially the line of reasoning proposed by us before in [10]. We are working consequently in relativistic mean field approach, with nucleon spectral function ρ^A in the impulse approximation (because the time of electron–parton scattering is much shorter than the time of nucleon–nucleon interaction). On the other hand, we include effect of Fermi motion of nucleons inside the

[1] See [9] for one of the first attempts in this direction.

nucleus as part of the corresponding parton primordial distribution [10]. It is done through the nucleonic mass in medium M_m, which differs from the mass of free nucleons M. The important feature of such approach is good agreement with experimental data. This should be contrasted with the recent calculations [14], which apparently fail in explaining the EMC effect in terms of modified nuclear distributions.

Why the nucleon mass is different in the medium? Let us follow the physical picture [10] where parton momenta are assumed to have some primordial distribution inside the hadron at rest. This distribution is either modelled by a statistical relativistic noninteracting gas model [11] or calculated from a spherically symmetric Gaussian distribution with a width derived from the Heisenberg uncertainty relation. The momenta of sea partons are assumed to follow similar Gaussian distribution but with a width dictated by the presence of virtual pions in hadron[2]. In order to fit experimental data the widths of partonic distributions should be decreased by 5 % when going to nuclear case ([10]). In the present approach, we are not changing the form of ρ^A, but we will find how to modify the nucleon mass entering nucleon structure function $F_N^2(x)$ through the Bjorken variable x introduced above. In the frame of Relativistic Mean Field (RMF) model of the nucleus [12] in the relativistic Fermi gas model approximation [2], the ρ^A is given by:

$$\rho^A(y_A) = \frac{4}{\rho}\int \frac{d^4p}{(2\pi)^4} S_N(p^0,\boldsymbol{p})\left[1+\frac{p_3}{E(p)}\right]\delta\left[y-\frac{(p_0+p_3)}{\mu}\right], \qquad (2)$$

where factor $(1+p_3/p_0)$ represents relativistic correction [16][3].

We encounter now the following dilemma. Whereas on the partonic level the SF should be calculated using partonic degrees of freedom, one encounters serious problem of proper treatment of forces binding nucleons in nuclei on this level. On the nuclear level they are described by exchange od mesons, which on the partonic level are just highly correlated quark-antiquark states. However, in deep inelastic collisions we see primordial partons inside the nucleus rather then the exchanged mesons. We shall therefore model binding effects by suitable changes in the primordial parton momenta distributions. In practice it amounts to changing the sea parton contributions in nuclear matter. We can perform it by using similar gaussian distribution as for free nucleons, but we have to change their width dictated

[2] Actually, similar results could be obtained using statistical model for nucleon SF which provides the primordial parton distributions as functions of partons four momenta [11].

[3] Eq. (2) was obtained for the RMF form of the nucleon spectral function: $S_N = n(p)\delta(p^0-(E(p)+U_V))$ with $E(p)=\sqrt{(m+U_S)^2+\boldsymbol{p}^2}$. From previous phenomenological investigations using RMF approach one deduces that typical values to be used are: $U_S = -400$ MeV (ρ/ρ_0) and $U_V = 300$ MeV (ρ/ρ_0) at $\rho_0 = 0.17\mathrm{fm}^{-3}$ [17].

by the presence of virtual pions in hadron. These changes affect only $x < 0.2$ region because there is no big momentum transfer from valence quarks to virtual mesons in nuclear medium [13], as we argued in the previous section. To produce the changes in SF for larger x, which are clearly visible in experiment, we shall follow the idea introduced in [10]. Namely, we shall include partonic motion in the expression for nucleon energy p^0 (*i.e.* its mass in rest frame in the medium), which is different from the rest energy of free nucleon, what changes accordingly the experimentally accessible Bjorken variable $x = x_{\mathrm{Bj}} = \frac{Q^2}{2p\cdot q}$. Notice that for the fixed resolution, $Q^2 = Q_0^2$, it is equal to $x = x_{\mathrm{LC}} = \frac{k^+}{p^+}$, *i.e.*, to the light cone nucleon rest frame variable. The change of the nucleon rest energy (mass) in the medium is usually connected with nucleon off shell behavior due to the nucleon–nucleon interactions. However, in our case the elementary interaction with parton is very short in comparison to average distance between nucleons inside the nucleus. We have therefore to treat nucleons in the deep inelastic process in the same way as the whole nucleus, *i.e.*, as objects on the energy shell:

$$\sqrt{P_A^2} \equiv M_A \xrightarrow{\text{rest}} P_A^+ \,, \qquad \sqrt{p^2} \equiv M_m \xrightarrow{\text{rest}} p^+ \,, \tag{3}$$

where M_m is the mass of nucleon in the medium (equal to p^+ component in the nucleon rest frame). In order to calculate M_m we shall consider the nuclear longitudinal component P^+ as sum of all quark momenta (because the quarks are almost massless therefore $k_{Ai}^+ = \sqrt{\vec{k}_{Ai}^2}$). Neglecting non nucleonic degrees of freedom we have:

$$\frac{1}{A}\sum_{i=1}^{A} k_{Ai}^0 = \frac{M_A}{A} \equiv M + \varepsilon = \int d^3p \sqrt{{M_m}^2 + \vec{p}^{\,2}} \,, \tag{4}$$

where $\varepsilon \simeq -8$ MeV is the usual nuclear mass defect. Instead of integrating over nucleon momentum we introduce quantity $E_{\mathrm{Fermi}} \simeq 0.6 \left(\sqrt{M_m^2 + \vec{p}_{\mathrm{F}}^{\,2}} - M_m\right)$, which is the average non-relativistic kinetic energy of nucleon in the nuclear matter obtained for uniform distribution with Fermi momentum p_{F}, and finally we have:

$$M_m \cong M + \varepsilon - E_{\mathrm{Fermi}} \,. \tag{5}$$

Therefore in the nuclear medium characterized by ε and E_{Fermi} the rest energy $M_m = \sum_i k_{Ni}^0$ of nucleons takes effectively value different from the nucleon mass M. It can be thought as sum of the corresponding partonic energies k_{Ni}^0 expressed in the rest frame of nucleon (*i.e.*, they differ from k_{Ai}^0 in (4)). When used in definition of x, such M_m accounts for the effect of Fermi motion of nucleons inside the nucleus. In this way we are now able to combine the influences of the Fermi motions emerging from both the nuclear (y) and nucleonic (x) levels. In what follows we shall use simplified form of Eq. (2):

$$\rho^A(y_A) = \frac{3}{4}\frac{v_A^2 - [y_A - (1+\eta)]^2}{v_A^3}\,, \tag{6}$$

where y_A takes values allowed by the inequality:

$$0 < (1+\eta) - \frac{p_{\rm F}}{M+\varepsilon} < y_A < (1+\eta) + \frac{p_{\rm F}}{M+\varepsilon}\,. \tag{7}$$

The parameter η measures effectively depletion of the longitudinal momentum of nucleon in the medium. Notice that for $M_m = M$ one has expecting small value of $\eta = \frac{\varepsilon}{M+\varepsilon}$.

4. Results

As seen in Fig. 1, the nuclear dependence without medium mass corrections (5) ($\eta \simeq 0.01$) is too weak to reproduce data (*cf.* dashed line in Fig. 1, which is similar to the negative results of [2] and [14]).

On the other hand, when M_m is given by (5) we can transfer the change of Bjorken x in in F_2^N to the following change of parameter η of ρ^A:

$$\eta = \frac{2\varepsilon - E_{\rm Fermi}}{M+\varepsilon}\,. \tag{8}$$

The results for the ratio $R(x) = F_2^{\rm Fe}(x)/F_2^D(x)$, calculated for two different constant average nuclear densities $n_{\rm nucl}$ are presented in Fig. 1. They include our nucleon mass modification[4]. Solid line corresponds to $n_{\rm nucl} = .096$ ($p_{\rm F} = 0.95$ fm^{-1} and $\eta \simeq -0.03$), dash dotted line corresponds to $n_{\rm nucl} = .12$ ($p_{\rm F} = 1.2$ fm^{-1} and $\eta \simeq -0.04$). Notice that agreement with data in the region is now much better. It is mainly related to the change of nucleon mass in the deep inelastic regime nuclear medium, *i.e.*,to $M_m \simeq 915$ MeV.

The relatively good fit to the EMC data can be improved further, by adding contribution from mediating nuclear forces between nucleons (*cf.* variant B in Fig. 2) to describe the small $x \le 0.25$ the pion SF was added like in [9]. The allowed small admixture of total momentum carried by pion excess in the medium [14] $(p_\pi^+)_{\rm av}/M_A = 1\%$. This excess will reduce the nucleon momenta but it should be already included in η (8). The direct scattering on additional pions improves our agreement with experimental

[4] Notice that introduction of M_m means rescaling of the variable x. We could therefore formally perform instead x rescaling, rescaling of y by factor $M_m/M \simeq 0.97$ and obtain the same result

data for small $x \simeq 0.2$; see dotted curve in Fig. 1. The main effect, however, is connected with the value of nucleon mass in the nuclear medium $M_m \simeq 915$ MeV. We would like to stress at this point that such reduction in nucleonic mass bound in nucleus is compatible with recent observation [15] of similar reduction of invariant mass in the decay spectrum of delta particles[5].

5. Summary

We have obtained good fit to experimental data in the interesting region of variable $x_A > 0.1$ by suitably modifying the nucleon mass in the medium. This modification depends on the value of Fermi momentum p_{F} and nuclear mass defect parameter ε [6]. Although such subtle changes of nucleon mass is difficult to measure inside the nuclear medium due to the presence of final state interactions, some recent observations of decay spectrum of delta particles seem to suggest that similar reduction (~ 20 MeV) of its invariant mass exists. The corresponding momentum sum rule is now given by the following formula:

$$\frac{\frac{1}{A}\int F_2^A(x_A)dx}{\int F_2^N(x)dx} = \frac{M_m}{M}\int y_A \rho^A(y_A)dy_A \simeq 97\%\,. \tag{9}$$

The main effect is produced by the nucleon mass change which causes depletion of momenta carried by quarks by $\simeq (96-97)\%$. Only small part $\simeq 1\%$ of it can be described by additional "nuclear" pions, the rest will change the balance with gluon momenta in the nucleus.

The resulting nucleon mass is slightly smaller and the pion is mass eventually slightly bigger (when shifted from 140 MeV to 150 MeV in the medium in order to tune the EMC ratio for small x region). This can be signature of the chiral restoration scenario [18] — the nucleons are pushed towards a partially deconfining phase. Presented mechanism is different from the conventional nuclear physics, where the nuclear bindings are coming only from the meson field.

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[5] Such measurement of the delta mass in possible due to its composite nature. For nucleon such measurement is impossible but the mechanism of mass reduction is practically the same.

[6] When viewed from the RMF theory perspective, all this corresponds to some effective modification of the scalar part of the nucleon single particle potential [2].

REFERENCES

[1] B. Bodek, J.L. Ritchie, *Phys. Rev.* **D23**, 1070 (1981); R.G. Arnold *et al.*, *Phys. Rev. Lett.* **52**, 727 (1984); M. Dasu *et al.*, *Phys. Rev. Lett.* **64**, 2591 (1988).

[2] M. Birse, *Phys. Lett.* **B299**, 188 (1993); J. Rożynek, *Int. J. Mod. Phys.* **E9**, 19 (2000).

[3] D.F. Geesaman, K. Saito, A.W. Thomas, *Annu. Rev. Nucl. Part. Sci.* **45**, 337 (1995).

[4] C.J. Carlson T.J. Havens *Phys. Rev. Lett.* **51**, 261 (1983).

[5] A. Edin, G. Ingelmann, *Phys. Lett.* **B432**, 402 (1998).

[6] S.J. Brodsky, H.C. Pauli, S.S. Pinsky, *Phys. Rep.* **301**, 2 (1998).

[7] A. Alde *et al.*, *Phys. Rev. Lett.* **564**, 2479 (1990).

[8] J.B. McClelland etal, *Phys. Rev. Lett.* **69**, 582 (1992).

[9] M. Staszel, J. Rozynek, G. Wilk, *Phys. Rev.* **D34**, 405 (1986).

[10] J. Rożynek, G. Wilk, *Phys. Lett.* **B473**, 167 (2000) and in Proc. of the International PANIC conference *Nucl. Phys.* **A** (2003), in print.

[11] Y-J. Zhang, L-M. Yang, B.-Q. Ma, *Phys. Lett.* **523**, (2001).

[12] B.D. Serot, J.D. Walecka, *Adv. Nucl. Phys.* Vol. **16** (1986); L.S. Celenza C.M. Shakin in *Relativistic Nuclear Physics*, World Scientific, Singapore 1986.

[13] G.E. Brown etal, *Nucl. Phys.* **A593**, 295 (1996).

[14] G.A. Miller, A. Schmit, *Phys. Rev.* **C65**, 055206 (2002).

[15] T. Matulewicz *et al.*, *Eur. J. Phys.* **A9**, 467 (2000).

[16] L.L. Frankfurt, M.I. Strickman, *Phys. Lett.* **183B**, 254 (1987).

[17] H. Jung, G.A. Miller, *Phys. Lett.* **B200**, 351 (1988).

[18] T. Hatsuda, T. Kunihiro *Phys. Rep.* **247**, 2479 (1994); G. Brown, M. Rho *Phys. Rep.* **363** (2002).