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COHERENT DENSITY FLUCTUATIONS AND EMC- EFFECT

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The EMC experimental results for ^{12}C and ^{56}Fe are interpreted within the coherent density fluctuation model in which nucleon-nucleon correlations and binding effects are taken into account. The nuclear structure functions for values of the scale variable x near unity are calculated as well.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Когерентные флуктуации плотности и ЕМС-эффект

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Экспериментальные данные глубоконеупругого рассеяния лептонов на углероде и железе интерпретируются в рамках модели когерентной флуктуации ядерной плотности с учетом связанности нуклонов и нуклон-нуклонных корреляций. Рассчитаны ядерные структурные функции в граничной области однонуклонной кинематики.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

1. The existing theoretical approaches which describe the nuclear structure functions $F^A_{1,2}(x)$ and explain their differences from the corresponding functions of free nucleons (EMC-effect) can be conventionally divided into two classes/1/. The first of them assumes the change of nucleon quark distributions in nuclei at the expense of a possible change of the Q^2-evolution conditions for the nuclear structure functions in the nucleus (Q^2-rescaling)/2/, the nucleon Fermi-motion being neglected. In this approach the nuclear structure functions at a point x and Q^2 are expressed in terms of nucleon structure functions $F^N_{1,2}(x)$ at the same x but at another Q^2, i.e. $F^A_{1,2}(x, Q^2) = F^N_{1,2}(x, \xi Q^2)$. The free parameter ξ can up to now neither be calculated theoretically nor

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determined from independent experiments. For this reason, in this approach ξ is chosen from the condition for the best fit of the experimental data (EMC, BCDMS, SLAC). The second class explains the difference between $F^A_{1,2}(x, Q^2)$ and $F^N_{1,2}(x, Q^2)$ on the basis of the internuclear motion of nucleons accounting for the off-mass-shell effects. The nucleon quark distributions are taken to be the same as for free nucleons. This type of approaches is based on the well-known fact that the properties of the quasiparticles-nucleons differ from those of the free nucleons. In particular, the bound nucleons have an effective mass depending on the shell energy. This leads to the renormalization of the scaling variable $x \Rightarrow m/m^*x$ (x-rescaling)[3]. These approaches seem to be more preferable as they do not contain free parameters. It has to be emphasized that the proper consideration of the single-particle state characteristics in them leads also to a good desctiption of the (e, e'p)-reactions[4]. In both cases (deep-inelastic scattering and (e, e'p)-reactions) the main idea is to investigate scattering on the deeply-bounded nucleons. The characteristics of deep-hole nuclear states, such as spectral functions, widths and centroid energies (as well as some other nuclear quantities: nucleon momentum distributions and cross sections of particle and ion scattering on nuclei) have been successfully described[5] in the framework of the coherent density fluctuation model (CDFM) suggested in[6]. The aim of the present work is to apply the CDFM to the problems of the deep-inelastic scattering (DIS) of leptons on nuclei (EMC-effect). In addition, we will consider the behaviour of the nuclear structure function in the region of larger values of x ($x > 0.6$, x being the light cone variable), where experimental data already exist[7]. Of particular interest is the region of x near unity. It is known that for larger values of x ($x \sim 1.2 \div 3$; cumulative processes in hA-collisions[8]) the main contribution to the nuclear structure functions comes from the multiquark states[9], the short-range NN-correlations[10], etc. To fix the parameters of such mechanisms, it is very important to know their relative contributions in the boundary region $x \sim 1$, where the role of the Fermi-motion of binding nucleons is still comparable with those of the mentioned mechanisms. In this case the nuclear structure function is sensitive to the choice of the spectral function (or of the momentum distribution).

2. In the impulse approximation the nuclear structure function $F^A_2(x)$ can be connected with the nucleon structure function $F^N_2(x)$ by the convolution formula[11]:

$$F^A_2 = \int_{x_N}^{A} \rho(y) F^N_2(x_N/y)dy, \qquad (1)$$

where $x_N = M_A/mx_A$, M_A and m are the nuclear and nucleon masses respectively. The function $\rho_N(y)$ has the meaning of the nucleon distribution probability in the nucleus where the nucleon is carryng out a part y of the total momentum. The explicit expression for $\rho_N(y)$ in the general relativistic case is unknown. This function has to obey two conservation conditions:

$$\int_0^A \rho_N(y)dy = A \quad \text{(baryon conservation law)} \tag{2}$$

$$\frac{1}{A}\int_0^A \rho_N(y)ydy = \langle y\rangle \tag{3}$$

Eq. (3) is related to the energy conservation law. If the nucleus only consists of nucleons, it is obvious that $\langle y\rangle = 1$. Otherwise, $\langle y\rangle < 1$. In the impulse approximation $\rho_N(y)$ is related to the nuclear spectral function $S(k, \omega)$ which is interpreted as a probability to find a particle with a momentum k in the initial nucleus as after its removal the residual nucleus has an excitation energy ω:

$$\rho_N(y) = \int \frac{d^3k}{(2\pi)^3} d\omega S(k, \omega)(1 - k_z/m)\delta(y - k\_/m), \quad \text{with} \tag{4}$$

$$\int \frac{d^3k}{(2\pi)^3} d\omega \; S(k, \omega) = A; \; k_- = m + \omega - k_z.$$

Eq. (4) involves the effects of binding nucleons through the energy dependence of the spectral function $S(k, \omega)$ and the delta-function. It can be seen that $\rho(y)$ from (4) satisfies the condition (2). As for the condition (3) it can be easily obtained that:

$$\langle y\rangle \cong 1 + \langle\omega\rangle/m, \quad \text{where } \langle\omega\rangle = \frac{1}{A}\int \frac{d^3k}{(2\pi)^3} S(k, \omega)\omega d\omega. \tag{5}$$

Here one can see from (5) the violation of the energy conservation law. It is obviously due to the binding effects. Since the nucleus can be treated as a system of interacting nucleons and mesons, it is natural that a part of the total nuclear momentum is carried out by mesons. It means that eq. (3) is only a part of the total energy conservation law.

It should be noted that expression (4) differs from the one in[3] by the flux factor $1 - k_z/m$ which in our case appears automatically owing to the nonrelativistic reduction of the relevant relativistic expressions[12]. The necessity of the inclusion of this factor into calculations was discussed also in ref.[13,14]. The flux factor does not change the general normalization of the spectral function in (4) and, consequently, does not violate the baryon conservation law (2). The inclusion of this factor in our calculations leads to a small deviation in the final results.

In the standard nuclear shell model the spectral function $S(\mathbf{k}, \omega)$ is just a single-particle momentum distribution. To explain the EMC-effect, it is necessary to take into account in the spectral function more complicated nuclear excitations, as is shown in ref.[3]. For this purpose it is convenient to use the spectral function $S(\mathbf{k}, \omega)$ from ref.[5,6] which describes the main characteristics of nuclei, energy and momentum distributions. In this case the momentum distribution is close to the theoretical values obtained by other authors[15] in their microscopical calculations, including nucleon-nucleon correlations.

In this paper we use the expression for the spectral function obtained in the framework of the CDFM[5,6]:

$$S(\mathbf{k}, \omega) = \frac{16\pi r_0^3}{3} \frac{\alpha}{2|\mathbf{k}|} \frac{|f(r_0)|^2}{\sqrt{\mu(\omega - E_f)}}, \tag{6}$$

where $r_0 = \alpha/|\mathbf{k}|\sqrt{(\omega - E_f)/\mu}$, $\alpha = (9\pi A/8)^{1/3}$. The values of the parameters E_f and μ are taken from[5]: $\mu = -50$ MeV and $E_f = -8$ MeV. It is shown in the CDFM[6] that the function $|f(r_0)|^2$ is related to the nuclear density distribution by the expression:

$$|f(r_0)|^2 = -\frac{4\pi r_0^3}{3A} \left(\frac{d\rho(r)}{dr}\right)_{r=r_0} . \tag{7}$$

Eq. (7) holds for monotonically decreasing density distributions. The function $|f(r_0)|^2$ can be determined by means of nuclear density distributions obtained from the analyses of the electron scattering on nuclei. In our case we use the symmetrized Fermi-type distribution with values of the parameters R (half-radius) and b (surface thickness) obtained from the electron experiments[16]. Then

$$|f(x)|^2 = \frac{4\pi x^3}{3Ab} \rho_0 \left\{ \frac{e^{-(x+R)/b}}{(1+e^{-(x+R)/b})^2} - \frac{e^{(x-R)/b}}{(1+e^{(x-R)/b})^2} \right\}, \tag{8}$$

where $\rho_0 = 3A/\left\{4\pi R^3 \left[1 + \left(\frac{\pi b}{R}\right)^2\right]\right\}$.

It was shown in ref. [5] that the theoretical results of the CDFM are in a good agreement with the experimental data for the hole nuclear state spectral functions extracted from (e, e'p)-reactions [4].

3. The structure function $F_2^A(x)$ for ^{12}C and ^{56}Fe nuclei has been calculated in the framework of CDFM using eqs.(1), (4), (6)-(8). For the $F_2^N(x)$ we use the parametrization [12]:

$$F_2^N = \frac{5}{18} x^{0.58} [2.69 + 1.56(1-x)] (1-x)^{2.7} + \frac{12}{9} 0.167(1-x)^7 \tag{9}$$

The spectral function (6) has been calculated using the following values of the parameters R and b: R = 2.214 fm, b = 0.488 fm for ^{12}C and R = 4.054 fm, b = 0.600 fm for ^{56}Fe. The ratio $F_2^A(x)/F_2^N(x)$ in the cases of ^{12}C and ^{56}Fe is presented in fig.1 and fig.2 respectively. It can be seen that the theoretical results of CDFM (with the account of the flux factor — solid line and without it — long-dashed line) are in a good agreement with the experimental data in the region $0.3 \leqslant x \leqslant 0.7$. We present also (short-dashed line in fig.1) the result for ^{12}C [17] obtained by using the one-particle spectral function calculated in the Hartree approximation with Skyrme forces. The shapes of the ratio in two cases

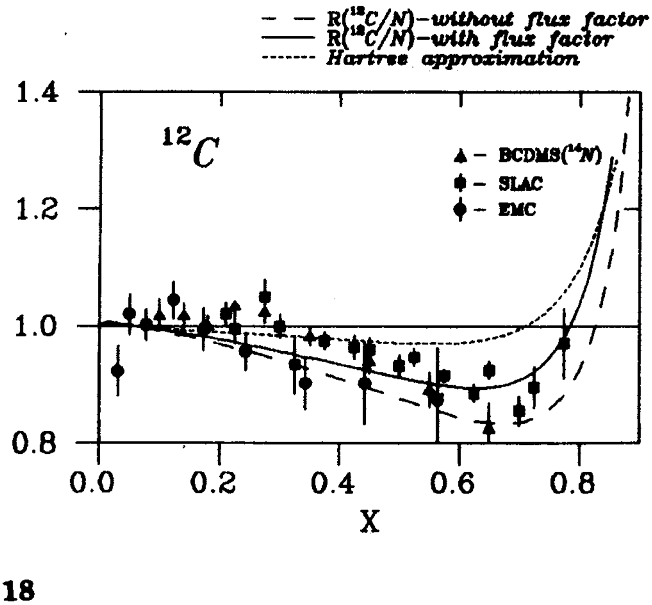

Fig.1. The ratio $F_2^{12C}(x)/F_2^N(x)$ calculated in the CDFM (with the account of the flux factor — solid line and without it — long-dashed line), and in the single-particle Hartree approximation with Skyrme forces (short-dashed line). The experimental data are taken from [18-20].

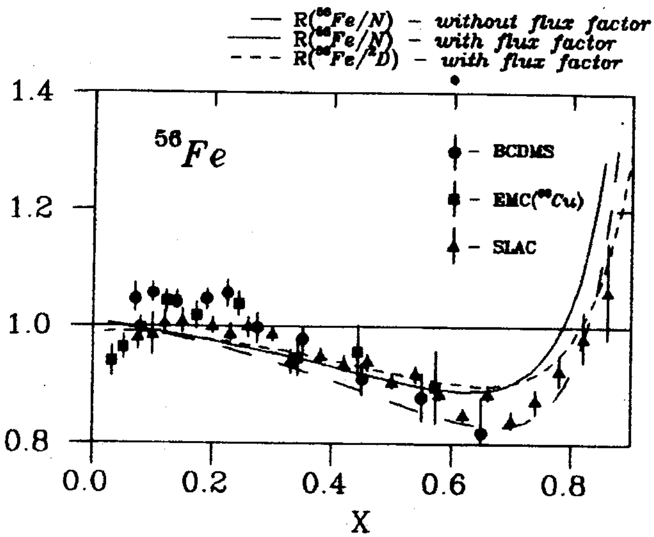

Fig.2 The ratio $F_2^{56Fe}(x)/F_2^N(x)$ calculated in the CDFM (with the account of the flux factor — solid line and without it — long-dashed line). The experimental data are taken from [18-20].

(CDFM and Hartree approximation) are close to each other. However, the depths of the minima are different. The behaviour of the nuclear structure function in the intermediate region of the variable x ($0.3 \leqslant x \leqslant 0.7$) is essentially determined by the value of $\langle\omega\rangle$ (5). In fact, expanding $F_2^N(x/y)$ in (1) near $\langle y\rangle$ (the point of $\rho_N(y)$ maximum):

$$\frac{1}{A} F_2^A(x) \cong F_2^N(x/\langle y\rangle) + \frac{1}{2}(\langle y^2\rangle - \langle y\rangle^2)\frac{\partial^2}{\partial\langle y\rangle^2} F_2^N(x/\langle y\rangle) + \ldots,$$

and, substituting $\langle y\rangle$ (5) we can estimate $F_2^A(x)$:

$$F_2^A(x) \approx F_2^N(x/(1 + \langle\omega\rangle/m)). \qquad (10)$$

Thus it is clear that the discrepancy between the results of CDFM and of the single-particle approach is due to different values of $\langle\omega\rangle$ used in the two models. The CDFM calculations give $\langle\omega\rangle \cong -38$ MeV which is in accordance with the results of refs. [3], whereas in the Hartree approximation $\langle\omega\rangle \approx -20$ MeV.

In fig.3 the absolute value of the structure functions for a nucleon and for ^{56}Fe (calculated within the CDFM and in the approach with the Fermi-motion but without nucleon binding effects) are given. It is seen that the CDFM curve in the region $0.9 \leqslant x \leqslant 1.2$ is substantially lower than the curve only with the nucleon Fermi-motion. In our opinion, this result might be of importance for the future experiments giving the nuclear structure functions in the region $x \geqslant 1$.

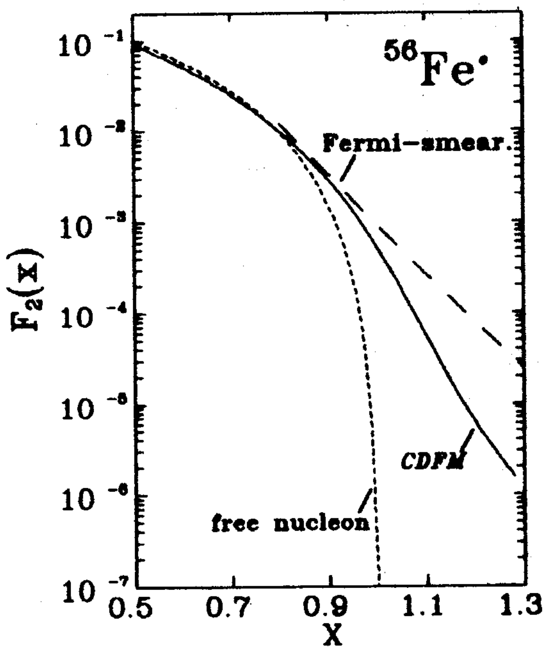

Fig.3. The absolute values of structure function $F_2^N(x)$ for the nucleon (short-dashed line) and for ^{56}Fe calculated in the CDFM (solid line) and in the approach accounting for the Fermi-motion without nucleon binding effects (long-dashed line).

4. In conclusion we note that the present CDFM calculations describe the EMC experimental results. This is a further confirmation of the Vagradov hypothesis/3/ about the role of the deep bounded nucleons in DIS reactions. On the other hand, the relative simplicity of the spectral function expression (6) allows one to apply the CDFM to analyse the DIS experimental data, to study relative contributions of other mechanisms and, also, to predict the behaviour of the structure functions near $x \simeq 1$.

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