QUARK DISTRIBUTION IN NUCLEI

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ABSTRACT

Some salient features of the limiting fragmentation of nuclei in cumulative region substantiating extraction of the nuclear structure functions from hadron reactions are discussed. Complementarity of information provided by lepton and hadron probes is pointed out. The QCD-based approach to the nuclear quark distribution in the lepton deep inelastic scattering is outlined which necessitates additional sea in nuclei.

1. INTRODUCTION

A study of the quark degrees of freedom in atomic nuclei is of interest from many points of view. First and foremost, it has a direct bearing on most acute problem of modern theory - the behaviour of QCD at large distances. The interaction of nucleons provides a possibility of the formation in nuclei of the multi-quark clusters. The properties of these clusters define the short-range part of the NN-potentials and the nuclear wave functions, which are of prime importance for the nuclear physics as a whole. The experimental investigation of the spatial and momentum distributions of partons in the short-lived multiquark configurations is possible only in the reactions of leptons and hadrons with nuclei at high energies. It will give a unique information on the unusual objects that may be considered as an admixture of new phase cells - quark - gluon plasma - in the nuclear matter. There is now a great interest in this new phase of the hadronic matter and the main hopes of its formation in a "macro-volume" (of an order of the nuclear volume) are related to the ultra-relativistic heavy ion collisions. It is evident that a reliable diagnostics of this new phase of matter requires knowledge of all mechanisms of nuclear reactions with large energy-momentum transfers taking into account all existing in nuclei under the ordinary condition configurations of the fundamental constituents of the hadronic matter - quarks and gluons. Therefore, the detailed study of the quark-gluon composition of nuclei is an indispensable part of building the complete theory of hadrons on the basis of QCD.

2. HADRON REACTIONS AND STRUCTURE FUNCTIONS OF NUCLEONS AND NUCLEI. CUMULATIVE EFFECT

The deep inelastic scattering of leptons on hadrons is a traditional and most reliable means to measure the structure functions (i.e. the quark momentum distributions in hadrons). The nuclear targets were customarily used with the aim to extract the nucleon structure functions. A widespread belief about the nuclear effects was to consider them as not very interesting and significant in most cases, or as rather reliably understood within the traditional notions (the impulse approximation, Fermi-motion etc.) stemming from the nonrelativistic quantum mechanics applied to the problem of the A=Z+N-interacting nucleons. This attitude seems to be distinctly changed when the results of the European muon collaboration (EMC) [1] on the ratio of the heavy nucleus (Fe) structure function to that of the deuterium turned out in sharp disagreement with expectations derived from the standard theory. We wish to stress, however, that long before the EMC data, the point of view alternative to the above-mentioned beliefs was put forward and developed. Namely, on the basis of observing the limiting fragmentation of nuclei in the high-energy hadron-nucleus collisions the clear-cut statement was made that the structure functions of nuclei are the qualitatively new objects in the physics of hadrons not reducing to the nucleon ones and thus well-deserving the special studies (see, e.g., the lectures by A.M.Baldin [2] and V.K.Lukyanov [3] at the precedent JINR-CERN Schools). The parton model and approximate scaling in the hard ($Q^2 \gg m^2$, $\nu = E_\ell - E_\ell' \gg m$, $0 \leq x \equiv Q^2/2m\nu \leq 1$) lepton-nucleon interactions are derived from the mechanism of the incoherent scattering of leptons on the point-like quarks. What justifies the application of the parton picture and measurability of the structure functions in the "soft" hadronic inclusive reactions $a + b \to c + X$ with small values of $\langle p_{\perp c} \rangle \simeq 0.4$ GeV? It is natural to expect that the production cross-section of hadron c should be proportional to the probability to find, in one of the initial hadrons, the group of partons $\{i\}$ with the quantum numbers of c and total longitudinal and transversal momentum fractions $\sum_i x_i$ and $\sum_i \vec{p}_{\perp i}$, the same as x_c and $\vec{p}_{\perp c}$. One should also invoke the "soft hadronization" hypothesis which means that the colour neutralization does not result in significant energy-momentum redistribution between newly produced hadrons. These qualitative arguments underlie a number of the recombination or fragmentation models [4] relating the inclusive cross-section $E_c\, d\sigma/d\vec{p}_c(a+b \to c+X)$ and the structure function of a hadron a (or b) in its fragmentation region ($x_c > 0.3$; $x_c = (p_0^c + p_z^c)/(p_0^a + p_z^a)$). As $x \to 1$ the experimental distribution has the form $d\sigma/dx \sim (1-x)^\kappa$. The mean values of the exponent κ for the meson production $p + h \to M(q\bar{q}) + X$ are $\kappa(p \xrightarrow{h} M(u,\bar{q})) \simeq 3.2$ and $\kappa(p \xrightarrow{h} M(d,\bar{q})) \simeq 4.0$)(one can obtain this by averaging over many experimental values collected in the review article [4]). These values correspond to fragmentation of proton into meson M containing the valence u - or d-quark respectively and by the soft colour neutralization assumption should be proportional to the u - and d- quark distribution in the parent proton: $u_v(x) \sim (1-x)^{\kappa(u)}$, $d_v(x) \sim (1-x)^{\kappa(d)}$. It turned out that both the ratio $d_v(x)/u_v(x) \sim (1-x)$ and the numerals $\kappa(u) \simeq 3$ and $\kappa(d) \simeq 4$ are very close to values found in the ℓN -reactions for the "current" quark distributions in proton [5]. Now, we turn to the inclusive hadron-nucleus reactions where the fast mesons M and nucleons N are emitted in the nucleus fragmentation region.

To explore the deep short-range nuclear structure, the cumulative particle production is most adequate, i.e. the particle production in the region kinematically forbidden for the reaction on the quasi-free nucleons. Exploring the cumulative reactions at high and intermediate energies uncovers a number of general and universal features which specify this new region of the hadron interaction physics [6-8].

1. Starting from the relatively low energy of incident particles $E_{lab} \simeq$ 4-5 GeV the limiting fragmentation of atomic nuclei is observed in the reactions $a + A \to c + X$, $a = \gamma, \ell, \pi, p, d, He.., c = \pi, K, N$ i.e. the shape of the fragment distributions is independent of energy and the type of incident particle.

2. The inclusive cross-sections are parametrized for $P_{\perp c} \simeq 0$ in the form

$$E_c \frac{d\sigma}{d\vec{p}_c} = f(A, x) = A^{\alpha(x)} \cdot G(x) \tag{1}$$

$$G(x) = G_0^{(c)} \cdot \exp(-x/\langle x \rangle), \langle x \rangle \simeq 0{,}14 \tag{2}$$

where the scaling variable is, in high-energy limit, $x = A(P_0^c + P_z^c)/(P_0^A + P_z^A)$ with the Z-axis chosen along the incident particle momentum. By definition, $x \geqslant 1$ specifies the cumulative region. For the meso-production in the "pre-cumulative" region $\alpha(x) \cong 1 - 1/3 \cdot (1-x)\,\theta(1-x)$, $\theta(x) = \begin{cases} 1, & x \geqslant 0 \\ 0, & x < 0 \end{cases}$, in Eq. (1), for $x \geqslant 0.6$. The numerical values of G_0 may be very different for various reactions, e.g. $G_0^p \gtrsim 10^2 \cdot G_0^\pi$ while $\langle x \rangle$ appears to be universal, thus providing the smooth fall of the x-distribution without observable steps at the border of different "cumulativity" order (x = 1,2,3,...).

3. The "cross-section per nucleon"$(E_c/A)(d\sigma/d\vec{p}_c)$ increases for p and π in a similar manner till A $\lesssim$ 20, then the pion yield is freezing at $\alpha_\pi(x) \simeq 1$ while that of protons continues to grow (roughly as A^{α_p} , $\alpha_p \simeq 1.4$) up to heavy nuclear-target. The normalized cross-section $(E_N/\sigma_{inel}^{aN}) \cdot (d\sigma/d\vec{p}_N\,(a + A \to N + X))$ has a similar A-dependence for any incident particle a and to 20-30% - accuracy does not depend at all on the initial particle: $a = \gamma, \ell, \pi, p, \ldots$

4. For the cumulative nucleon yields the isotopic and isotonic effects have been observed, that is the independence of proton (neutron) yield of increasing the number of neutrons (protons) in the given isotope (isotonic). A kind of the "isosymmetrization" has also been observed, i.e. an approximate equality of the cumulative proton and neutron yields in sharp contrast with a relative number of neutrons and protons in heavy nuclei. The ratio of the sufficiently energetic ($P_{lab} \geqslant$ 300 MeV) pion yields $R = \pi^+/\pi^-$ is also very close to 1.

Practically all attempts to explain the accumulated experimental facts start from the general idea of existence in nuclei of the short-ranged (and short-lived) multiquark (or multibaryon, $B \gtrsim 2$) clusters, or configurations [9-13], the cumulative particles being just the fragmentation products of these clusters. The immediate task for theory now is to obtain the necessary properties of these objects and to embed them into a general structure of the traditional nuclear physics. The second aspect includes the calculation of the probability amplitudes C_K to find the $3K$ quark clusters in the nuclear wave functions:

$$\Psi = \Psi(AN) + \sum_{K=2}^{A} C_K \Psi(3Kq;(A-K)N) \tag{3}$$

The modern searches for the solution of these problems are based on the same model concepts and methods that are applied in the derivation of the nucleon-nucleon potentials and the NN-scattering phases. In brief, the region of the nucleon interaction is divided into the "internal" and "external" parts. In the internal region all quarks of the system are localized and governed by the appropriately chosen dynamics while the external region is described with the traditional nuclear physics in terms of nucleons interacting via the pion exchanges and the corresponding Yukawa-type potentials. Information about the internal region can be introduced, e.g., into the logarithmic derivative of the nucleon-channel wave function at the surface separating two regions [14,15]. In this framework the internal quark dynamics has been approximated by models of the MIT-bag-type, and it was found [15] for the probability of the 6q-bag in deuteron $w^d_{6q} \simeq 2\%$.

An alternative class of models appears as the appropriate generalization of the interpolation methods used in describing the clustering phenomena in the nonrelativistic nuclear physics. Sewing up two regions with different dynamics is realized by the effective interpolating potential

$$V(r) = V_{int}(r)\,\theta(r_0 - r) + V_{ext}(r)\,\theta(r - r_0) =$$

$$= \sum_{i<j=1}^{6} V_{qq}(i,j)\cdot\theta(r_0 - r) + \Big[V^m_{NN}(r) + \sum_{i<j=1}^{3} V_{qq}(i,j) + \sum_{i<j=4}^{6} V_{qq}(i,j)\Big]\,\theta(r - r_0) \tag{4}$$

where V^m_{NN} is the long-range "tail" of the meson potentials, V_{qq} are the qq- interaction potentials, $r_0 \simeq 2r^N_0 \simeq 0.8$ fm (r^N_0 is the radius of the quark dimension of a nucleon). The calculation within the nonrelativistic constituent quark model, using Eq. (4), gives $w^d_{6q} \simeq 6\text{-}7\%$ [3,11].

The detailed investigation and discrimination between the model-dependent structure of the internal, multiquark configuration wave functions is clearly of upmost importance and it may be provided only by the high-energy particle-nuclear reactions sensitive to short-distances between nucleons in nuclei. The first knowledge about the form of the momentum distribution of quarks in the multibaryon clusters has just been gained from the limiting nuclear fragmentation studies. That we really deal with the quark-parton structure functions of nuclei is suggested by theoretical arguments supported by experiment. In addition to what we have known from the hadron-hadron reactions, one more important circumstance should be stressed here. The universality of cumulative particle spectra gives evidence of the relative suppression, in the hadron-nuclear reaction of those factors which reveal themselves in dependence on energy and quantum numbers of incident particles of the inclusive spectra observed in some hadron-hadron reactions, thus hampering the interpretation of these data in terms of the single and universal characteristic of fragmenting hadron - its structure function.

The prediction [16] based on the nuclear fragmentation data of the essential features of the structure functions for the deep inelastic scattering of leptons on nuclei at $x \gtrsim 1$ was later confirmed by the experiment [17]. For large $x \gtrsim 1.5$ the hadronic reactions are the only source of information to date, and all findings from there may serve as the predictions to be verified in the forthcoming experiments with the lepton beams. The detailed comparison between the leptonic and hadronic data may also serve as the source of new information. As is well-known, there is a firmly established breaking of scaling, i.e. the quark distribution functions are Q^2-dependent: $q = q(x, Q^2)$. The structure functions are extracted from data taken usually at high $Q^2 \simeq 10\text{-}100\ \mathrm{GeV}^2$. But, what effective scale should the structure functions from the hadron reactions be reffered to? Most reasonably, this scale should be of the "natural" order of magnitude $Q_0^2 \sim \langle P_{\perp q}^2 \rangle \sim O(1\ \mathrm{GeV}^2)$ i.e., of an order of the mean transverse momentum of the current quarks in hadrons or multiquark clusters. If so, then to compare the similar quantities in the similar conditions, one should evolve the measured $q = q(x, Q^2 = 10 - 100\ \mathrm{GeV}^2)$ backward to Q_0^2 with the help of the evolution equations of QCD. In a sense, the momentum distributions of the spectator-quarks from the "soft" hadron-hadron or hadron-nucleus processes are more adequate to check the model wave function dominating the static properties of hadrons and, in turn, dominated by the nonperturbative mechanisms of QCD. Low effective scale Q_0^2 should be reflected in more "hard" gluon distribution and it would be interesting to find its experimental implications.

3. DEEP INELASTIC SCATTERING OF LEPTONS AND NUCLEAR EFFECTS

Nuclear effects in deep inelastic scattering of leptons were communicated for the first time by the BCDMS collaboration [17] at large $x > 1$ and the EMC [1] at $0.05 \leq x \leq 0.65$. The results [17] in cumulative region are still waiting for a confirmation and those of the EMC have largely (except , possibly, $x < 0.2$ region) been confirmed by other experiments [18] (recall the factor $A^{\alpha(x)}$ in Eq. (1) showing qualitatively the same phenomenon which was later pinpointed by the EMC). These results have initiated the multitude of theoretical works (see, e.g., the reviews [18-21] and references therein) in which the data are described (or fitted) within a broad variety of models. To clear up really essential factors for subsequent interpretation it seems reasonable to choose a starting point as close as possible to fundamental theory - - QCD. Nuclei are nothing but the quark-gluon systems and all methods developed for analysis of the nucleon structure functions (the moment method, sum rules, etc.) are entirely applicable to them. Having this in mind we shall follow basically the approach of Ref. 22.

At large Q^2 QCD defines evolution of the parton distributions

$$\dot{q}_v(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int dy\, dz\, P_{qq}(y) q_v(z,Q^2)\, \delta(yz-x) \tag{5a}$$

$$\dot{q}_i(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int dy\, dz \left[P_{qq}(y) q_i(z,Q^2) + P_{qG}(y) G(z,Q^2)\right] \delta(yz-x) \tag{5b}$$

$$\dot{G}(x,Q^2) = \frac{\alpha_s(Q^2)}{2\pi} \int dy\, dz \left[P_{Gq}(y) q_s(z,Q^2) + P_{GG}(y) G(z,Q^2)\right] \delta(yz-x) \tag{5c}$$

where $\dot{q}(x,Q^2) = dq(x,Q^2)/d\ln Q^2$, $\alpha_s(Q^2)$ is the running coupling constant, P_{qq}, P_{qG}, P_{Gq}, P_{GG} are the known "splitting" functions which are calculated via perturbation theory and are universal ones, i.e. independent of whether the partons reside in a nucleus or in a free nucleon. Universality of the P's leads to an important relation for power moments of the valence quark distributions

$$\frac{\dot{V}_A(n,Q^2)}{V_A(n,Q^2)} = \frac{\dot{V}_N(n,Q^2)}{V_N(n,Q^2)} \tag{6}$$

from where

$$V_A(n,Q^2) = T_A(n) V_N(n,Q^2) \tag{7}$$

with

$$q_v(n,Q^2) \equiv V(n,Q^2) = \int dx\, x^{n-1} \left(q_i(x,Q^2) - \bar{q}_i(x,Q^2)\right). \tag{8}$$

N (A) refers to the structure functions of a free nucleon or nucleus (divided by A), i labels the flavour of quarks, the limits of integration in (8) are $0 \leq x \leq 1$ (A), and T_A is not yet specified. Returning from moments to functions we have

$$\begin{aligned} V_A(x,Q^2) &= \int_0^A d\beta\, dy\, T_A(\beta) V_N(y,Q^2)\, \delta(\beta y - x) = \\ &= \int_x^A \frac{d\beta}{\beta} T_A(\beta) V_N\left(\frac{x}{\beta},Q^2\right) \equiv T_A \otimes V_N \end{aligned} \tag{9}$$

Normalization of $V_N(x,Q^2)$ and $V_A(x,Q^2)$ to the unit baryon number gives

$$\int_0^A T_A(\beta)\, d\beta = 1 \tag{10}$$

Positiveness and normalization of $T_A(\beta)$ suggest to identify it with the effective distribution of the nucleon longitudinal momentum fraction in nuclei.

For the singlet distributions including the sea quarks and gluons the corresponding formulas are more complex due to "nondiagonal" transitions of sea quarks to gluons and vice versa. However, one can find such linear combinations $f^{\pm} = q_S + C^{\pm} G$, $q_S = \sum_i (q_i + \bar{q}_i)$ for which the analog of Eq. (9) is written in the diagonal form

$$f_A^{\pm} = T_A^{\pm} \otimes f_N^{\pm} \tag{11}$$

Extremely important relation is the total energy-momentum sum rule

$$f^{+}(n=2;\, Q^2) = \int dx \cdot x \left[q_S(x,Q^2) + G(x,Q^2) \right] = 1 \tag{12}$$

which gives

$$\int_0^A \beta\, T_A^{+}(\beta)\, d\beta = 1 \tag{13}$$

(We neglect terms of the order ε_B / m , ε_B being the binding energy per nucleon). In the general case $T_A^{+} \neq T_A$, $T_A^{-} \neq T_A$. By analogy with (9) and (11) one can introduce the relations berween "pure" $q\bar{q}$ -sea and gluon distributions in nuclei and a free nucleon:

$$S_A(x,Q^2) = \int_x^A \frac{d\beta}{\beta} T_A(\beta) S_N\left(\frac{x}{\beta}, Q^2\right) + S_A'(x,Q^2) \tag{14}$$

$$G_A(x,Q^2) = \int_x^A \frac{d\beta}{\beta} T_A(\beta) G_N\left(\frac{x}{\beta}, Q^2\right) + G_A'(x,Q^2) \tag{15}$$

where S_A' and G_A' are additional, "collective" nuclear sea which can be shown to absent only in the case $T_A^{+} = T_A^{-} = T_A$. But just this case is at variance with data if we require validity of exact sum rules (10) and (13). For nuclei taken as weakly-bound system of (basically) nonrelativistic nucleons $T_A(\beta)$ should look like the distribution sharply peaked at $\beta \simeq 1$ with dispersion of an order of $O(p_F^2/m^2)$, p_F is the Fermi-momentum. Now, in expression for the structure function

$$F_2^A(x,Q^2) = \int_x^A d\beta\, T_A(\beta) F_2^N\left(\frac{x}{\beta}, Q^2\right) \tag{16}$$

we expand $F_2^N\left(\frac{x}{\beta}\right)$ around $\beta \simeq 1$ and obtain for point x_0 of interception of ratio $R = F_2^A / F_2^N$ with the value R=1:

$$x_0 = 2\,(1 + \bar{\delta}/\overline{\delta^2})/(1 + \kappa + \bar{\delta}/\overline{\delta^2}) \tag{17}$$

where

$$\bar{\delta} = 1 - \int_0^A \beta\, T_A(\beta)\, d\beta = 1 - \frac{\langle x_v \rangle_A}{\langle x_v \rangle_N} \tag{18}$$

$$\overline{\delta^2} = \int_0^A (1-\beta)^2\, T_A(\beta)\, d\beta \tag{19}$$

and we use, for simplicity, $F_2^N \sim (1-x)^\kappa$.
If $\bar{\delta} = 0$ (following from $T_A^+ = T_A$ and (13)) and $\kappa = 3$ we have $x_0 \simeq 0.5$ in contradiction with $x_0^{exp} \simeq 0.85$. One should evidently diminish the mean momentum fraction of valence quarks $\bar{\delta} > 0$ which in turn requires an additional sea in nuclei. The needed values $\bar{\delta} \simeq \overline{\delta^2} \simeq 0.04 - 0.05$ are easily implemented within the simplest nuclear model - the "shifted" Fermi distribution

$$T_A(\beta) = \frac{3}{4}\left(\frac{m}{P_F}\right)^3 \begin{cases} P_F^2/m^2 - (1-\beta-\bar{\delta})^2, & \text{if } |1-\beta-\bar{\delta}| < P_F/m \\ 0 & \text{, otherwise} \end{cases} \tag{20}$$

which reproduces well the dependence of F_2^A / F_2^N on x in the range $0.3 \leq x \leq 1$. The momentum fractions of the additional nuclear sea should compensate the momentum lost by valence quarks

$$\Delta\langle x_V \rangle + \Delta\langle x_S \rangle + \Delta\langle x_G \rangle = 0 \tag{21}$$

$$\Delta\langle x_V \rangle = \langle x_V \rangle_A - \langle x_V \rangle_N = -\bar{\delta}\cdot\langle x_V \rangle_N \tag{22a}$$

$$\Delta\langle x_S \rangle = \langle x_{S'} \rangle_A - \bar{\delta}\cdot\langle x_S \rangle_N \tag{22b}$$

$$\Delta\langle x_G \rangle = \langle x_{G'} \rangle_A - \bar{\delta}\cdot\langle x_G \rangle_N \tag{22c}$$

that is

$$\langle x_{S'} \rangle_A + \langle x_{G'} \rangle_A = \bar{\delta} \tag{23}$$

To have an impression of relative values of $\langle x_{S'} \rangle$ and $\langle x_{G'} \rangle$, we turn to the second moment of structure functions calculated in Ref. 22 according to the EMC data [1)]

$$I_2^A - I_2^N = \int dx\,[F_2^A(x,Q^2) - F_2^d(x,Q^2)] = \tag{24}$$

$$= \frac{2}{9}\langle x_{S'} \rangle_A - \frac{2}{9}\bar{\delta}\cdot\left[\langle x_S \rangle_N + \frac{5}{4}\langle x_V \rangle_N\right] \simeq (0{,}65 \pm 0{,}06)\cdot 10^{-2}$$

Using the values [5] $\langle x_S\rangle_N + \frac{5}{4}\langle x_V\rangle_N = 0.12 + \frac{5}{4}\cdot 0{,}35 \simeq 0.56$ and $\bar{\delta} \simeq 0.045$, one gets $\langle x_{S'}\rangle_A \simeq 0.05$, $\langle x_{G'}\rangle_A \simeq -0.005$. If we want the additional $q\bar{q}$-pairs and gluons to be "materialized" into pion's sea, it would be most natural to have $\langle x_{S'}\rangle_A = \langle x_{G'}\rangle_A \simeq 0{,}5\cdot\bar{\delta}$. But in this case the integral (24) will acquire the zero value

$$I_2^A - I_2^N \simeq 0 \tag{25}$$

which appears to be more consistent with the SLAC data [23a,b] and new BCDMS data for ^{14}N-nucleus [23c].

As was pointed out in a recent work [24] the slight ($\simeq$ 5%) renormalization of the EMC data at small $x \lesssim 0.2$ admissible by their experimental uncertainties would result in fulfilment of the asymptotic sum rule (25). In Figure 1 below we sketch a possible x-dependence of nuclear effects in the deep inelastic scattering.

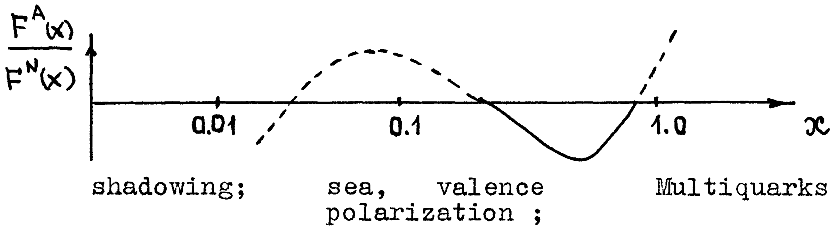

Figure 1
Possible x-dependence of nuclear effects

4. CONCLUSION

The immediate perspectives for a future research work are more or less evident. A complete separation of sea, valence and gluon distributions in nucleons and nuclei using e , μ , ν , $\bar{\nu}$ data, massive di-lepton production, J/ψ - photo-(lepto-) production remains to be the first priority task. The probing of the cumulative region by leptons should be accomplished. A detailed, varying Q^2 exploration of low x region including transition to the shadowing regime is needed. Further continuation and development of nuclear studies by incident hadron beams including the polarized beam-target facilities, cumulative jets and particle-correlation measurements, the resonance production (both the OZI allowed and forbidden) are indispensable. To conclude, the investigation of the quark-gluon structure of nuclei opens new horizons in both nuclear physics and strong interaction theory, focusing attention on the colour dynamics in multiparticle systems. A very broad spectrum of the proposed theoretical models, each claiming to be "QCD-motivated", speaks to only how much remains to be done for elaboration of the universal, selfconsistent, and more tightly bound to fundamental QCD, theory of the considered processes.

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