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THE QUARK-PARTON STRUCTURE FUNCTIONS OF NUCLEI

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The aim of the present talk is to discuss the experimental data which testify in favour of the fact that the distribution of quarks and gluons in nucleons which are embedded in nuclei essentially differs from the free nucleon case. In other words, we shall give evidence for the fact that the quark-parton structure functions of nuclei[1] are independent (irreducible to one-nucleon) objects of hadron physics and shall discuss the presently available properties of these functions.

Typical momenta for quark confinement effects in hadrons are as small as about 300 MeV/c. The quark interactions at small distances are well described on the basis of asymptotic freedom. The parton model which has been given grounds in QCD is, as a matter of fact, an impulse approximation. These ideas underlie the additive quark model and the quark recombination model for which there are good analogs in nuclear physics (stripping and pickup). There naturally arises the question as to to what extent the atomic nuclei may be considered as quark-gluon systems rather than multinucleon systems. In other words, what is the role of the quark and gluon degrees of freedom in nuclei. The Dubna physicists are being engaged in this problem since 1970 (see, e.g., refs.[2,6]) on the basis of extensive experimental studies with relativistic nuclear beams from the Synchrophasotron.

In this talk we consider the atomic nuclei as ordinary hadrons laying aside the problems of correspondence between the model used and the proton-neutron nuclear model. In the region of small momentum transfers the quark-parton structure functions must turn into structure functions in which the nucleons should be thought of as partons.

In just the same way as before[1] we extract the structure funtions from the data on limiting fragmentation of nuclei.The properties of the structure functions thus obtained were recently confirmed in experiments on deep inelastic scattering of leptons on nuclei[3,4,5].

The collisions of hadrons with small momentum transfers and large values of the scale variable x in the region of limiting fragmentation are described as a result of individual collisions of the quarks of a fragmenting hadron with the quarks and gluons of the target. The spectator quarks which avoided collision carry the momentum fraction x of the fragmenting hadron. Hadronization of the quark to a hadron-fragment (color neutralization) is taken to be soft and the hadron-fragment distribution is assumed to coincide with the quark-spectator distribution. Thus we may consider that the inclusive cross section of the process

$$I + II \to 1 + \dots \qquad (1)$$

in the region of limiting fragmentation of, for example, nucleus II is of the form

$$E_1 \frac{d\sigma_I^{II}}{d\vec{P}_1} = C_q^1 \cdot \sigma_q^I \cdot G_{II/q}\ (x, P_{1\perp}^2)\ , \qquad (2)$$

where E_1 and P_1 are the energy and momentum of the particle fragment. We shall mainly use the data of the Stavinsky's group [6] for the case when particle 1 is a pion and particles I are protons and deuterons. The quantity $G_{II/q}\ (x, P_T^2)$ is the quark-parton structure function of nucleus II. More than twenty different elements have been used as fragmenting nuclei II. C_q^1 is the constant characterizing hadronization of quark q into hadron 1, σ_q^I is the cross section of the process in which quark q from hadron II passes throughout target I having avoided collision. The quantities $G_{II/q}\ (x, P_T^2)$ are, in their physical meaning, universal momentum distributions of quarks q in nucleus II. The same functions $G_{II/q}$ are used to express the cross sections of different reactions with large momentum transfers proceeding on this nucleus. In particular, the cross sections for deep inelastic scattering of leptons on nucleus II

$$\ell + II \to \ell' + \dots \qquad (3)$$

and the cross sections for lepton pair production

$$I + II \to \ell^+ + \ell^- + \dots \qquad (4)$$

are expressed in terms of the functions $G_{II/q}(x, P_T^2)$ and the cross sections for electromagnetic quark interactions (see, e.g. [7]). From eq. (2) it follows that the ratio of the inclusive cross sections for limiting fragmentation of different nuclei II' and II into identical particles (in our case, into pions) is equal to the ratio of their structure functions

$$E_1 \frac{d\sigma_I^{II'}}{d\vec{P}_1} \Big/ E_1 \frac{d\sigma_I^{II}}{d\vec{P}_1} = \frac{G_{II'/q}\ (x, P_{1\perp}^2)}{G_{II/q}\ (x, P_{1\perp}^2)}\ . \qquad (5)$$

In relativistic nuclear physics, it is common to assign the cross sections and kinematical variables to one nucleon of the nucleus participating in the reaction; namely, the colliding energy is

characterized by an invariant quantity $\epsilon = \frac{(P_I \cdot P_{II})}{m_I\, m_{II}}$. Here and below P_i are the four-momenta and m_i are the particle masses. In a frame where, e.g., nucleus I is at rest

$$\epsilon = \frac{E_{II}}{m_{II}} = \frac{E_{II}/A_{II}}{m_0}$$

$m_0 = 931$ MeV is the atomic mass unit, A_{II} the atomic weight of nucleus II. The limiting fragmentation corresponds to independence of $E_1 \frac{d\sigma}{d\vec{P}_1}$ of the energy ϵ per nucleon of the incident nucleus. Accordingly the Bjorken variable X is expressed in terms of the momentum per nucleon P_{II}/A_{II}:

$$X = -\frac{q^2}{2(P_{II}/A_{II} \cdot q)} = -A_{II} \cdot \frac{q^2}{2(P_{II} \cdot q)} = -A_{II}\, x\ , \qquad (6)$$

where q is the four-momentum transfer in process (3), X changes in the limits $0 \le X \le A_{II}$. Processes occurring at $X > 1$ are given the name cumulative. For reaction (2) the variable X with due account of mass corrections is of the form (particle 1 is a pion):

$$X = A_{II} \frac{(P_I \cdot P_1) - m_\pi^2/2}{(P_I \cdot P_{II}) - m_I\, m_{II} - (P_{II} \cdot P_1)} \qquad (7)$$

and transforms into the variable (6) neglecting masses.

We consider the experimental facts [2,6,8] which testify in favour of the model (2).

1. The cross section for processes (I) in the range $X \sim 1$, $P_\perp \simeq 0$ is found to be no longer dependent on ϵ for $\epsilon \gtrsim 4$, that is, limiting fragmentation of nuclei begins at an energy of about 4 GeV/nucleon. This is in agreement with the short-range correlation radius in the rapidity space $\Delta y \sim 2$: $\epsilon = ch(y_I - y_{II}) \sim ch2 \approx 3.8$.

2. The cross section for process (I) in the range $4 \le \epsilon \le 400$ and $0.6 \le X \le 3.5$ is well approximated by a simple dependence [2,6]

$$E_1 \frac{d\sigma}{d\vec{P}_1} = \text{const}\ A_I^{1/3} \cdot A_{II}^{m(X)}\ \exp\left[-\frac{X}{\langle X \rangle}\right]. \qquad (8)$$

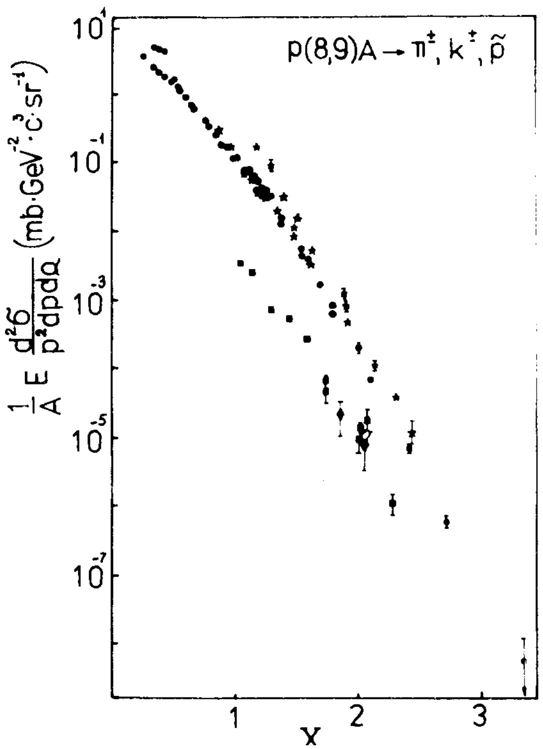

Fig.1. Symbols (•) denote the experimental data for π^+ mesons; (⋆) for K^+ mesons; and (■) for K^- mesons. The data of ref.[6] are shown for the pA interaction at ϵ = 9.54 (backward production for proton momenta 8.9 GeV/c and $P_\perp = 0$).

The parameter $\langle X \rangle$ does not depend within errors on the quantum numbers of cumulative particles and is equal to 0.14 to an accuracy of 10%. The quantity m(X) is equal to unity for X > 1 and $A_{II} > 20$ and for $0.6 \leq X \leq 1$ is approximated[2,6] by the dependence $m(X) = \frac{2}{3} + \frac{X}{3} < 1$.

According to the model (2) the $A_I^{1/3}$ dependence should be attributed to the cross section σ_q^I.

3. Within experimental errors, the cumulative production cross sections for pions and kaons for identical X are in the following remarkable relationship to each other (see fig.1):

$$E_1 \frac{d\sigma}{d\vec{P}_1}(\pi^-) \approx E_1 \frac{d\sigma}{d\vec{P}_1}(\pi^+) \approx E_1 \frac{d\sigma}{d\vec{P}_1}(K^+) \gg E_1 \frac{d\sigma}{d\vec{P}_1}(K^-).$$

This relation is a good evidence for the validity of model (2). As far as nuclei consist predominantly of quarks u and d, then the equality of the K^+ and π^+ cross sections should be viewed as a consequence of the fact that they are determined by the same structure function $G_{II/u}(X, P_\perp^2)$. In addition, it should be assumed that $C_d^{\pi^-} \approx C_u^{\pi^+} \approx C_u^{K^+}$. The fact that among the valence quarks bound in the nucleus there are no valence quarks bound in negative kaons just explains this inequality.

Agreement between experiment and the model (2) has made it possible to determine the properties of the quark-parton structure functions for $0.6 \leq X \leq 3.5$ and $P_\perp = 0$

$$G_{II/u}(X, 0) = \text{const}\, A^{m(X)} \exp[-\frac{X}{0,14}]. \qquad (9)$$

These properties turn out to be universal for various nuclei. In particular, eq. (9) has enabled us to predict[1] the results of the NA-4 experiment on deep inelastic scattering of muons on carbon. The structure function of a carbon nucleus extracted from experiments[3] in the kinematic range $50 \leq Q^2 \leq 280$ GeV^2 and $0.6 < X < 1.5$ is in good agreement with eq. (9). This experiment has confirmed some properties of the cumulative effect (X > 1), although it is doubtful whether one will succeed in obtaining X as large as from limiting fragmentation studies even by using large facilities offered by the NA-4 spectrometer.

Another important confirmation of our conclusions about the $G_{II/q}$ properties is the measurement of the structure function ratios for various nuclei[6].

We introduce the structure functions normalized to a nucleon

$$G^{\circ}_{II/q} = \frac{1}{A_{II}} G_{II/q}(X, P_\perp^2) \qquad (10)$$

and determine their ratio for different nuclei:

$$\frac{\sigma_{II'}}{\sigma_{II}}(X, P_\perp^2) = \frac{G^{\circ}_{II'/q}(X, P_\perp^2)}{G^{\circ}_{II/q}(X, P_\perp^2)}. \qquad (11)$$

Figure 2 presents the earlier obtained[6] experimental data on the structure functions of nuclei in the form of the ratio (11). The quantity $\frac{\sigma_{II'}}{\sigma_{II}}(X, P_\perp^2)$ for $A_{II'} > A_{II}$ is seen to have a characteristic minimum. In accordance with our approximation of the limiting fragmentation cross sections (8):

$$\frac{\sigma_{II'}}{\sigma_{II}}(X, P_\perp^2) < 1 \quad \text{for} \quad A_{II'} > A_{II} \quad \text{and} \quad X < 1. \qquad (12)$$

But at $X \to 1$, $\frac{\sigma_{II'}}{\sigma_{II}}(X)$ tends to unity.

It is important to note that the discussed A dependence of the cross section (8) of the type $A^{2/3 + X/3}$ for $X \lesssim 1$ in the limiting fragmentation region $\epsilon > 4$ has been confirmed by Schroeder et al[9]. It was lately discovered in the European Muon Collaboration experiments[4] and in experiments on deep

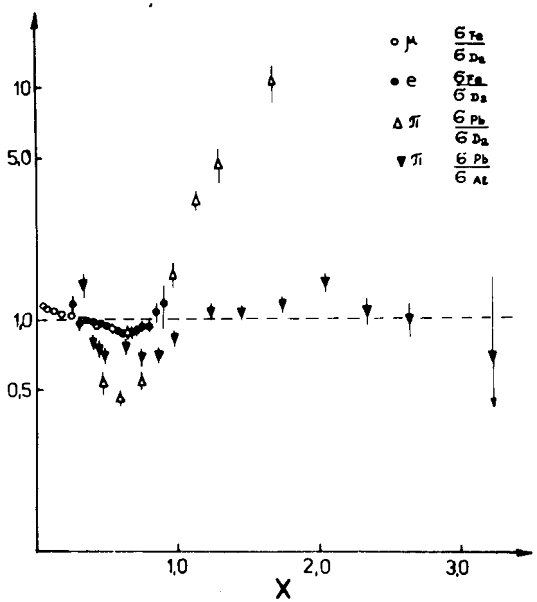

Fig. 2

inelastic ed and eFe scattering at SLAC [5]. Data from refs. [4,5] are also given in fig.2 (circles). Qualitative agreement of the $G_{II/q}$ data obtained in essentially different experiments and at different momentum transfers a good confirmation of the model and universality of the structure functions.

The cumulative region $X > 1$ is of special interest. In this region $\frac{\sigma_{Pb}}{\sigma_d}(X)$ much exceeds unity (see fig.2), while $\frac{\sigma_{Pb}}{\sigma_{Al}}(x)$ over the whole region $1 \le X \le 3$ is equal to unity. This fact is consistent with the idea about the cumulative effect as a result of interactions of multiquark configurations existing in the nucleus and containing the effective number of nucleons equal to X. In the deuterium nucleus there are no configurations including quarks from more than two nucleons, while the aluminium nucleus little differs, in this sense, from the lead nucleus. In ref. [6] the data on the ratio of the structure functions (11) for different nuclei are given in the form of a function of A:

$\frac{\sigma_A}{\sigma_{Pb}}$ (X = 1.3). It is important to notice that over the whole region $A < 20$ this quantity is essentially smaller than unity and decreases with decreasing A. This means that not only in deuterium, but also in all the lightest nuclei up to $A \approx 20$ the multiquark configurations are different from one another and strongly differ from the multiquark configurations in heavy nuclei.

CONCLUSIONS

1. The universal properties of the structure functions of nuclei as independent (irreducible to one-nucleon) objects

of hadron physics have been established in a wide range of the variables X, Q^2, A:

$$G(X, Q^2, A) = \text{const}\, A^{m(X)} \exp\left[-\frac{X}{\langle X \rangle}\right],$$

where $\langle X \rangle = 0.14$; m(X) is a weak function with minimum at $X \approx 0.5$; for $X > 1$ $m(X) \approx 1$.

2. The described properties of the structure functions give evidence for the existence of multiquark configurations in nuclei which differ essentially from the ones in free nucleons. They are important for the formulation of the quark theory of the nucleus and quantum chromodynamics of large distances. So far, attempts of constructing a theory for the observed effects make a rather restricted success (see refs. [10,11,12]).

Special attention should be paid to the work by Dar et al [13] in which in just the same way as in ref. [1] the authors have introduced the quark-partion structure function and have attempted to interprete it as a superposition of the free nucleon structure functions.

3. Neutrino and some muon experiments aimed at measurements of the nucleon structure functions are wrongly interpreted in literature because the underlying supposition

$$G_{A/q}(X, Q^2) = A\, G_{N/q}(X, Q^2)$$

contradicts the above-mentioned results.

To extract the QCD parameter Λ_{QCD} on the basis of evolution equations the quark parton structure functions of nuclei may be a better tool than the quark-parton structure functions of nucleons, since they are measured in a wide range of X and are free of troubles inherent in the range $X \approx 1$.

4. Of much importance are further measurements of the structure functions of nuclei in both deep inelastic scattering of leptons and the muon pair production (4) in a broad range of dimuon masses, especially in the region of high mass dimuons and near $X \sim 1$. Investigations of the dimuon pairs in the resonance region at $X > 1$ will make it possible to get information on cumulative production of vector particles and to test the theoretical assumptions about dynamic manifestations of integrals of motion [14]. The great interest is the study of dimuon pair production by polarized deuterons which gives a rather critical test of QCD. Large possibilities for further investigations in this domain are due to the intensive beams of relativistic nuclei ($\epsilon > 4$) from the Synchrophasotron and, especially, to the polarized deuteron beam available.

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Кварк-партонные структурные функции ядер

Существовавшие ранее и новые экспериментальные данные используются для обсуждения свойств структурных функций ядер как независимых /не сводимых к однонуклонным/ объектов адронной физики. Основные данные получены группой Ставинского в экспериментах по предельной фрагментации более чем 20 ядер от лития до урана. Обнаруженные свойства структурных функций свидетельствуют о существовании в ядрах мультикварковых конфигураций, существенно отличающихся от тех, которые имеются как в свободных нуклонах, так и в двух-, трех- и более нуклонных системах. Эксперименты по глубоконеупругому рассеянию лептонов на ядрах, проведенные группой НА-4 /ЦЕРН-Дубна/, Европейской мюонной коллаборацией и на ускорителе СЛАК,подтверждают выводы о структурных функциях ядер, сделанные на основе изучения предельной фрагментации ядер.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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The Quark-Parton Structure Functions of Nuclei

The previously available and new experimental data are used to discuss the properties of the structure functions of nuclei as independent (irreducible to one-nucleon) objects of hadron physics. The basic data have been obtained by the Stavinsky's group in experiments on limiting fragmentation of more than 20 nuclei from ^{7}Li to ^{238}U. The discovered properties of the quark-parton structure functions give evidence for the existence in nuclei of multiquark configurations which essentially differ from those present in both free nucleons and two-, three- and more nucleon systems. Experiments on deep inelastic scattering of leptons on nuclei performed by the CERN-Dubna NA-4 Collaboration, the European Muon Collaboration and at SLAC confirm the conclusions about the structure functions of nuclei drawn from nuclear limiting fragmentation studies.

The investigation has been performed at the Laboratory of High Energies, JINR.

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