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A.M.Baldin

THE QUARK-PARTON STRUCTURE FUNCTIONS OF NUCLEI

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At the XIX International Conference on High Energy Physics (Tokyo) in the talk devoted to multibaryon interactions at relativistic energies [1] there were given arguments in favour of the following conclusions:

- The limiting fragmentation of nuclei begins in nucleus-nucleus collisions at an energy 3.5-4 GeV/nucl.
- There exist universal regularities which describe the one-particle distributions in the cumulative region.
- Experiments show the large value of the cumulative particle polarization, strong A dependences of the cross sections, unusual dependences on the quantum numbers (flavors) and angles.
- The cumulative particle production is in an interesting accordance with the production of particles and hadron jets with large $P_\perp$ on nuclei.

These results show that we deal with new phenomena for the interpretation of which the quark degrees of freedom of the nucleus are important. At the same time, they show the invalidity of the attempts to describe the large momentum transfers to nuclei by taking into account the nucleon degrees of freedom alone. From the very beginning of studies of these phenomena [2] it was clear that the most probable and natural candidate for the cumulative effect theory is the quark-parton theory of hard collisions. The elements of this theory as applied to nuclear collisions [6] and some interesting conclusions were presented by Blokhintsev [3] at the Tokyo Conference. A detailed discussion of the general problems of the theory of hard collisions with large momentum transfers on the basis of the QCD application was given by Field [4] at the same Conference.

The quark-parton theory of hard collisions has been given grounds in QCD. Now we know how to calculate corrections to the naive parton model. Of a special importance is the description of quark hadronization. The problems of large momentum transfers, spin dependences, strong A dependences and quark recombination bear a direct relation to this problem and will be discussed at special sessions of the fortcoming XX Conference in Madison.

The aim of the present paper is to state our point of view on the above-mentioned problems, to give some new physical results obtained at Dubna and to discuss some especially urgent experiments.

The basic quantities of the hard collision theory are the functions of quark distribution in the hadron (in our case, in the nucleus), $G^h_q(\beta, P_\perp^2)$, and the functions of fragmentation of quarks to hadrons, $D^q_h(\beta, P_\perp^2)$, (in our case, multibaryon systems can be taken as particle-products). Here $\beta = \frac{E_q + P_q^z}{E_h + P_h}$ and, respectively, $\beta = \frac{E_h + P_h^z}{E_q + P_q}$ are the ordinary parton variables, $P_\perp^2$ is the squared transverse momentum of the particle-product. As far as there are some reasons to suppose [5] the existence of "reciprocity relation" $G^h_q(\beta, P_\perp^2) = D^q_h(\beta, P_\perp^2)$ then, as a matter of fact, we are discussing the properties of one function. We will mainly discuss the cumulative region, that is, the region $\beta > 1$.

The quantities E_h and P_h are the energy and momentum per one nucleon of the nucleus. In a system, where the fragmenting nucleus is at rest, this corresponds to $\beta = \frac{E + P^z}{m_p}$, m_p is the proton mass. The G properties in this region are analogous to those in the region of large transverse momenta, $P_\perp \geq 1$ GeV/c, therefore this group of phenomena is given the common name - nuclear collisions involving large momentum transfers.

Beginning with the first papers on the cumulative effect the invariant one-particle distributions in this region are written in the form

$$\frac{E}{\sigma_{in}} \frac{d\sigma}{d\vec{p}} = \sum_N P_N \cdot \rho_N(\beta, P_\perp^2) = \rho(\beta, P_\perp^2), \tag{1}$$

where σ_{in} is the inelastic collision cross section

$$\rho_N(\beta, P_\perp^2) = 0 \qquad N < \beta,$$

P_N is the probability of finding a configuration of N nucleons in the nucleus, N is the effective number of nucleons involved in the process. Since P_N is a very rapidly decreasing function, then eq. (1) can be given for small $P_\perp$ in the form

$$\frac{E}{\sigma_{in}} \cdot \frac{d\sigma}{d\vec{p}} = C \cdot \exp[-a\beta]. \tag{2}$$

The experimental data summed up in the talk [1] allowed the following parametrization of the formula (2):

$$E \frac{d\sigma}{d\vec{p}} = \text{Const}\, A_{II}^{1/3} A_I^m \exp[-a\beta], \tag{3}$$

where A_I and A_{II} are the atomic weights of the fragmenting nucleus and the target-nucleus, respectively.

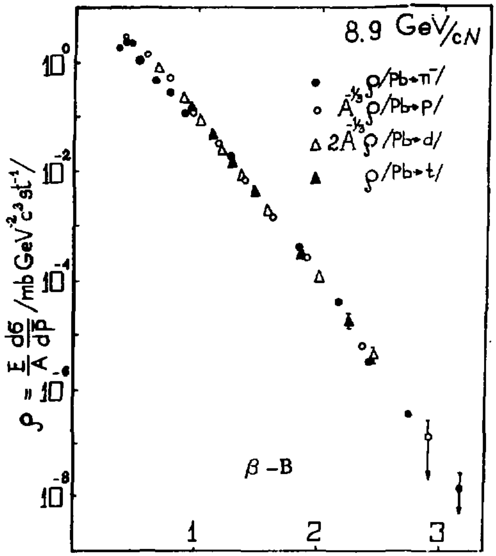

Fig.1

The parameter a was found to be no longer dependent on the colliding nucleus energy at an energy above 3.5-4 GeV/nucl., which was stressed in ref.[1] as the beginning of the limiting fragmentation of nuclei. This characteristic value was predicted on the basis of the general property of hadronic matter, that is, the correlation length value in the rapidity space.

The exponent m was predicted to be β dependent: $m \approx \frac{2}{3}+\frac{1}{3}\beta$. For $\beta > 1$, $m > 1$. Eq. (3) describes practically all the set of experimental data on the cumulative effect including the angular distributions of cumulative particles.

The assertion that the cumulative effect is the main source of information on the quark distribution in nuclei not only remained unchanged, but also became essentially deeper and more complete (see ref.[10]) *.

The universal dependence of the type of eq. (3) has been confirmed by subsequent experiments, among which the results of the Stavinsky group [7] are worth to be noted. In his experiments it was shown that the production cross section for the following cumulative particles: π, K, p, d, t can be described by the unique parameter a, that is, the latter is independent of the quantum numbers of cumulative particles, and appears to be the most important characteristic of quark distribution in nuclei (the functions G_q^h).These essential new experimental results are given in Fig.1 which shows the analogy of

* The quark-parton structure function of nuclei has recently been discussed by Dar and his co-workers [11] on the basis of the modified collective tube model. They have succeeded in describing a large amount of various experimental material relative to high-energy particle-nucleus collisions by means of this simple model.

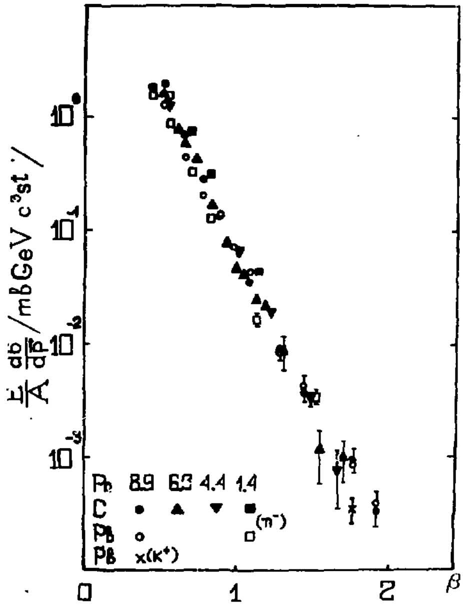

Fig.2

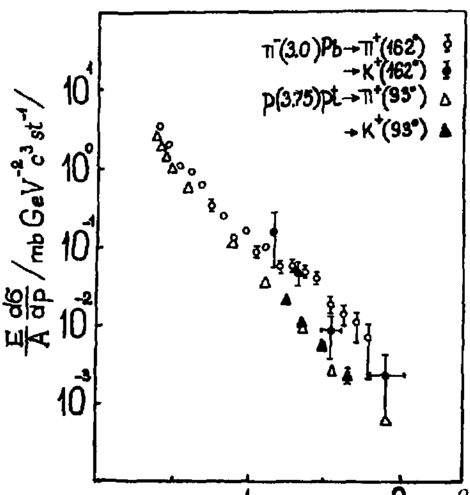

Fig.3

the processes of hadronization of quarks to "elementary" hadrons and nuclear fragments.

The dependence of $E\frac{d\sigma}{d\vec{p}}$ on β was retraced when $E\frac{d\sigma}{d\vec{p}}$ was changed by nine orders of magnitude. An approximate equality of $E\frac{d\sigma}{d\vec{p}}$'s for identical β for the π and K mesons is found to be the surprising and important result (Figs.1 and 3).

The important confirmation of the beginning of limiting fragmentation at an energy 3.5 GeV/nucl. is the obtaining of the data on the cumulative effect in the reactions $p + A \to 1 + X$ at an energy 400 GeV [3]. These data yield the same universal parameter a which was obtained by us earlier (see also paper /12/).

The complicated and unusual A dependences of the cumulative production cross sections, on the one hand, were still confirmed, and, on the other hand, exhibited new peculiarities. The most essential of them is the departure of the A dependence to the asymptotic regime. Deviations from the simple dependence of the type A^m, where $m = \frac{2}{3} + \frac{1}{3}\beta$, should be expected starting from the models suggested earlier. In fact, according to ref./1/ for P_N we take the binomial distribution which to a good accuracy can be presented in the form

$$\frac{A!}{N!(A-N)!} \cdot q^N (1-q)^{A-N} \approx C_1 \frac{1}{N!} A^{N/3} \exp[-(\frac{r}{r_0})^2 A^{1/3}] .$$

The exponential provides here a noticeable deflection from the simple exponential dependence A^m. However, using this formula we fail in describing the asymptotic regime discovered by the Stavinsky group (see Fig.4).

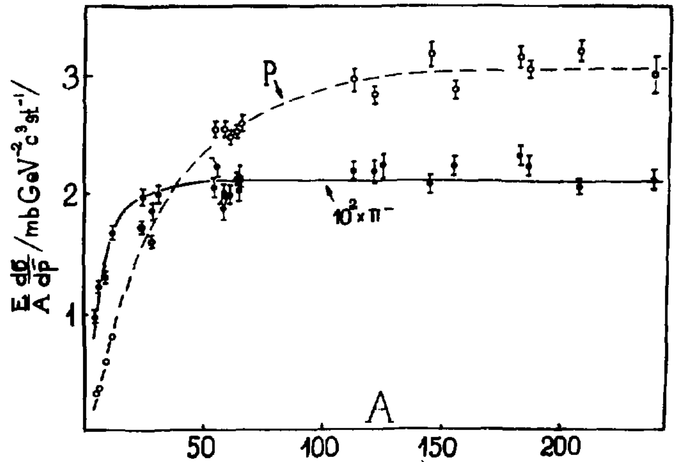

Fig.4

The A dependence of the quark-parton function of nuclear fragmentation is for the theory a still unsolved problem. As is shown by the data on the cumulative effect and the production of particles with large $P_\perp$ mentioned, the A and β dependences of G_q^h are not factorized. This is likely to indicate that the role of the effects of quark recombination to hadrons is essential. The important role of quark recombination follows also from the mentioned "reciprocity relation" $D(\beta, P_\perp^2) = G(\beta, P_\perp^2)$ according to which the experimentally discovered A dependence of the cumulative production cross section should identically be ascribed both to G and D. This idea may explain an essential difference of the A dependence for the cumulative particles with different quark composition, namely, the increase of the A dependence of the cross section by an additional factor $A^{B/3}$, where B is the baryon number of the cumulative particle.

It is interesting to note that a similar increase of the A dependence had been detected for the formation of nuclear fragments with $P_{\perp} \sim 1$ GeV/c [14]. Figures 5 and 6 show the data on production of nuclear fragments with large transverse momentum. The figures will illustrate the change of the A dependence of the cross section from the usual geometric $A^{2/3}$ to the $A^{m(P_{\perp})}$, in this case m reaches a value much larger than unity.

The important result is a new measurement of m in the A dependence of the cumulative Λ particle production cross section. From the experiment [13] of the Shakhbasian group m was found to be 1.49±0.18 instead of the earlier existing data of the Leksin group m = 0.56 ±0.08. The new data are in good agreement with the mentioned dependence of m on the baryon number of the cumulative particle.

The interpretation of the experimental data on the cumulative effect in terms of the quark-parton structure functions of nuclei strongly depends on the validity of the hypotheses on quantum number conservation in the process of the quark recombination to hadrons the check of which is very important.

In this connection polarization experiments are of a special interest. In ref. [9] it was proved that in the region of large momentum transfers we are interested in the quark helicity conserves in the hadronization. Measurements of the cumulative baryon and vector meson polarization are therefore measurements of the dependence of G_q^h and D_h^q on one more variable. For the time being, we have only rough estimates for

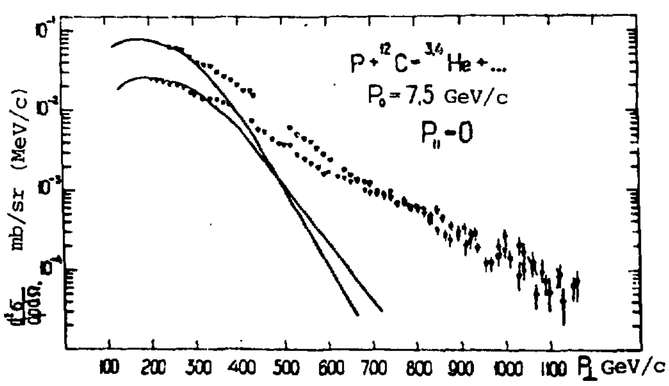

Fig.5

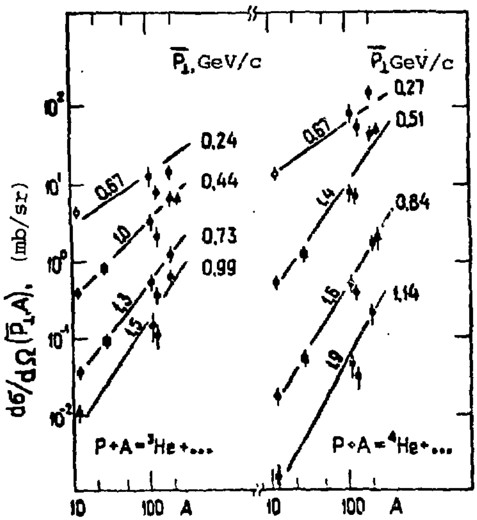

Fig.6

the cumulative proton and Λ hyperon polarization /1,3/ which show that it is large enough and reaches 100%. The quantitative study of the polarization phenomena in the cumulative particle production is one of the most urgent experiments in the domain of multibaryon phenomena. In particular, most attention should be paid to the study of the cumulative effect induced by polarized particles.

Experiments on measurement of quark distribution in nuclei, which are free of uncertainties caused by the quark recombination to hadrons are actually experiments on deep inelastic scattering of leptons on nuclei in the cimulative region. However, due to the smallness of the cross sections, the only apparatus at which such experiments are feasible is NA-4 at CERN. I have suggested /10/ to extract the relevant information from the existing experimental data on the reaction $\mu + {}^{12}C \to \mu + X$. Using the data on G_q^h given above it is not difficult to estimate the cross sections. The main dependence of the cross section on x in the region $0.6 \le x \le 2$ will be determined by a sharp exponential (3) with an exponent $a \approx \frac{1}{0.16}$. The fraction $\frac{\Delta\sigma}{\sigma}$ of the cross section for the Bjorken variable $x > \ell$ is estimated as

$$\frac{\Delta\sigma}{\sigma} \approx e^{-\ell/0.16} = \begin{cases} 2\cdot 10^{-3} & \text{for} \quad \ell = 1 \\ 1.2\cdot 10^{-4} & \text{for} \quad \ell = 1.5 \\ 0.6\cdot 10^{-5} & \text{for} \quad \ell = 2 \end{cases} .$$

From here it is seen that for the existing and planned statistics it is quite possible to measure the region x up to 2 by means of NA-4 which is of much interest not only from the point of view of direct measurements of quark-parton distributions in nuclei, but also from the point of view of the study of various effects at large Q^2. The latter purpose is the most significant for the NA-4 experiment. The data on the reaction $\mu + {}^{12}C \to \mu + X$, presented at the present Conference have been obtained on the basis of the assumption that the quark structure function $G(\beta, P_\perp^2)$ reduces to one-nucleon structure functions. This assumption contradicts the above-stated viewpoint since the data obtained on NA-4 correspond to $Q^2 \gg 1$ GeV^2.

CONCLUSION

1. The quark-parton structure functions of nuclei, $G(\beta, P_\perp^2)$, in the region $\beta > 1$ as independent (irreducible to one-nucleon) objects of the hadron physics became of much importance and are being studied both in theoretical and experimental aspects.

2. The universal character of the structure functions is defined not only by the earlier established limiting nuclear fragmentation beginning at an energy 3.5-4 GeV/A in relativistic nucleus collisions. The parameter $a = -\frac{d\ln\rho}{d\beta} \approx \langle\beta\rangle^{-1}$, which characterizes the longitudinal quark distribution, was found to be universal, independent of the quantum numbers of cumulative particles.

3. The parametrization of the A dependence of the D functions in the form A^m used earlier (where m was as large as 2) was found to be insufficient. There were observed asymptotic regimes in the A dependence:

$\sigma \propto A^1$.

The strong dependence of m (in the old parametrization) on the cumulative number β and the baryon number of a cumulative particle shows an interdependence (nonfactorizability) of these parameters.

4. An ever-growing background of experimental information on the cumulative particle production goes essentially beyond the framework of the results based on the quark-parton models of hard collisions and QCD.

5. Of a special value is the direct measurement of $D(\beta)$ functions in deep inelastic lepton-nuclear interactions and the study of polarization phenomena in the cumulative effect as sensitive methods for QCD checking.

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