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A.M.Baldin

THE RELATIVISTIC NUCLEAR PHYSICS

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The acceleration of deuterons at the Dubna synchrophasotron in 1970 showed that there are no difficulties of principle in obtaining beams of complex nuclei up to relativistic energies. Possible programmes of studies with such beams [1-2] were found to be very promissing. These studies are especially urgent due to the fact that the experiments in a qualitatively new range of energies of heavy-ion beams started in just the same period in which the most important ideas of strong interaction physics such as scale invariance, limiting fragmentation, quark-parton models and, after all, quantum chromodynamics, which pretends to play the role of a consistent strong interaction theory, were rapidly developed. The discovery of new particles and application of quark models for interpreting their properties have made the positions of the quark models much stronger. At present few people doubt that the quarks are good quasiparticles which should be used to describe hadrons at small distances. From the very beginning of the studies with relativistic nuclei it became evident that there must exist such a region of collisions of particles and nuclei with nuclei for the description of which it is necessary to go over from the quasiparticles-nucleons to the quasiparticles-quarks. In this paper we show that the presently available background of experimental information on relativistic nuclear collisions enables us not only to indicate exactly this region, but also to define the quark-parton function of relativistic nuclei in the most interesting region, the cumulative one. The quark matter or quark plasma is obviously the chief and most realistic candidate to the role of extreme states of nuclear matter which the present Conference is devoted to.

Attention will first be focused on the study of the effects associated with large momentum transfers to nuclei. Large momentum transfers to a system of nucleons (of the order of or larger than their mass) require a consistent relativistic approach and correspond to relative internucleon distances of the order of or smaller than the confinement radius where the quark degrees of freedom must be predominant. As a matter of fact, we are dealing here with the problems of the hadron physics and quantum field theory. Correspondingly, the methods and approaches in these investigations, both theoretical and experimental, are essentially an adaptation and development of the high-energy physics methods. These investigations go beyond the framework of the canonical nonrelativistic nuclear theory. Therefore the first section is devoted to the explanation of the basic notions and quantities of the relativistic nuclear physics. In the second section we give the most essential physical results and their analysis. The third one contains the description of the programme of investigations in the field of the relativistic nuclear physics carried out at the Joint Institute for Nuclear Research.

1. THE BASIC NOTIONS AND QUANTITIES

The region of multibaryon phenomena defined by the condition

$$\frac{m^2}{\vec{p}^{\,2}} \ll 1, \tag{1.1}$$

where $\vec{p}$ are the three-momenta of particles and m, their masses, is called by us the relativistic nuclear physics. In this region of importance is the production of new particles. The relativistic description of multiparticle states encounters the following difficulties: i) we have to deal with a variable number of particles and, consequently, with an infinite number of degrees of freedom; ii) a many-time formalism is needed; iii) it is impossible to separate the contributions of particles and antiparticles in a relativistic invariant manner, to separate the internal motion from the motion of the composite system as a whole. The description of states in the Fock space is the most adequate one to the relativistic nuclear physics since it can be used to define states with a variable number of particles and, at the same time, allows an interpretation similar to that of the wave functions in nonrelativistic theory. The Fock column defined on the hyperplane $t=0$ ("equal time") in the coordinate space is

$$\Phi = \begin{bmatrix} \Psi_1(x_1) \\ \Psi_2(x_1, x_2) \\ \cdots\cdots\cdots \\ \Psi_n(x_1, \ldots, x_n) \\ \cdots\cdots \end{bmatrix} \tag{1.2}$$

The squared functions $\Psi_n(x_1,\ldots,x_n)$ have the meaning of the probability density for n particles to be found in the system. It is not difficult to show (see, e.g., ref. [3]) that in the nonrelativistic case, when the Hamiltonian of the system commutes with the particle number operator, the Fock space disintegrates into subspaces. Each subspace has then its Schrödinger equation for an appropriate number of particles. While in the relativistic case, when the particle production and annihilation can occur, the Hamiltonian and the momentum operators do not commute with the particle number operator, neither do the Lorentz transformation operators. This means that in the Lorentz transformation the lines of the Fock column get mixed up and in different coordinate frames the composition of a moving object, e.g., a nucleus, will be different.

The number of the particles in a system depends on the momentum with which it moves. In this connection, of particular importance is the concept of coordinate frame moving with infinitely large momentum [4,5] (IMF). For a wide class of theories, a composite object in this frame becomes a set of almost non-interacting constituents and the consideration is completely analogous to that in the nonrelativistic case. This idea underlies the parton models [6] which have successfully been applied to the collisions of "elementary" hadrons.

This approach is analogous to the impulse approximation in nuclear physics: due to relativistic time dilation the characteristic times of the internal dynamics of the system are found to be much larger than the collision times. The collision cross section for a composite system is expressed in terms of that for a free constituent, the parton. Compared to the elementary particle, the nucleus in the relativistic energy region can successfully be thought of [1] as a parton gas since the life-times of the virtual nuclear state as an assembly of free nucleons are much larger than the life-time of the nucleon as an assembly of partons. Thus, the methods developed in the quark-parton models provide us with a basis for considering relativistic collisions involving nuclei and enable us to overcome the above-mentioned troubles of relativistic description of many-particle states.

The time development of the system is defined by the total energy which for a system of free particles is determined as

$$E = \sum_{i=1}^{n} \sqrt{\vec{p}_i^{\,2} + m_i^2}. \tag{1.3}$$

Let the motion along the axis z satisfy the basic criterion (1.1), then

$$E = \sum_{i=1}^{n} \sqrt{p_{iz}^2 + r_i^2 + m_i^2} \approx P_z + \sum_{i=1} \frac{r_i^2 + m_i^2}{2p_{iz}} \tag{1.4}$$

here and in what follows P is the total momentum of the system, and $\vec{r}_i^2 = p_{i\perp}^2 = p_{ix}^2 + p_{iy}^2$. It is seen that in a coordinate system, where $P_z \to \infty$ (IMF)[4], it is possible to divide the motion of the system into the motion as a whole and the internal motion.

It should be stressed that our approach is based on the following hypothesis: there exists such a P_z that all the internal and transverse momenta are much smaller than this quantity. It is convenient to work in the IMF with the light cone coordinates which are linked with the ordinary coordinates in the following manner:

$$\tau = \frac{1}{\sqrt{2}}(t' + z'); \quad x = x'; \quad y = y'; \quad \zeta = \frac{1}{\sqrt{2}}(t' - z'). \tag{1.5}$$

The energy-momentum variables conjugate to the latter are obviously found from

$$p_\mu x^\mu = H\tau + \eta\zeta + p_x x + p_y y \tag{1.6}$$

from where

$$H = \frac{1}{\sqrt{2}}(E - p_z); \quad p_x = p'_x; \quad p_y = p'_y; \quad \eta = \frac{1}{\sqrt{2}}(E + p_z).$$

It is convenient to write the transformation from the lab.system to the IMF in terms of the hyperbolic angle ω between the time axes of these systems

$$p_z = p'_z \operatorname{ch}\omega + E' \operatorname{sh}\omega,$$

$$E = p'_z \operatorname{sh}\omega + E' \operatorname{sh}\omega,$$

$$\vec{r} = \vec{r}'.$$

The case we are considering corresponds to $\operatorname{ch}\omega \to \operatorname{sh}\omega \to \frac{1}{2}e^\omega$.

In this case the transformation along the z axis assumes the form

$$\eta \to e^{\omega'}\eta; \quad \vec{r} \to \vec{r} \tag{1.7}$$

and the rotations around the x and y axes, the form

$$\vec{r} \to \vec{r} + \vec{V}\eta, \qquad \eta \to \eta. \tag{1.8}$$

Eq. (1.8) is analogous to the Galilean transformation, provided that η is an analog of the mass and $\vec{V}$ that of the relative motion velocity. This analogy becomes still more complete if we recall the expression for the energy in the IMF

$$H = \sum_{i=1}^{n} \frac{r_i^2 + m_i^2}{2\eta_i}. \tag{1.9}$$

The introduced notation and concepts make it possible to introduce the wave function of the multiparticle state in the IMF:

$$\Psi_{\eta P_\perp}(\eta_1, \vec{r}_1; \ldots; \eta_n, \vec{r}_n).$$

The invariance under the (1.7) and (1.9) transformations requires that all dependences on η_i and $\vec{r}_i$ occur through the variables $\beta_i = \frac{\eta_i}{\eta}$ and the variables $\vec{R}_i = \vec{r}_i - \frac{\eta_i}{\eta}P_\perp$. The wave function assumes then the form

$$\Psi_n = \Psi_n(\beta_1, \ldots, \beta_n; \ldots; \vec{R}_i \vec{R}_j \ldots), \tag{1.10}$$

$\beta_i = \frac{E_i + p_{iz}}{E + P_z}$ is a fraction of the momentum which is carried by subsystem (parton, nucleon, quark). The normalization of these functions is usually taken as

$$\langle \eta, \vec{r} | \eta', \vec{r}' \rangle = \eta\delta(\eta - \eta') \cdot \delta^2(\vec{r} - \vec{r}'). \tag{1.11}$$

The integration is performed over the invariant measure $\frac{d\eta}{\eta} d^2r$. In the introduced notation the normalization has the form

$$\sum_n \int \frac{d\beta_1 \ldots d\beta_n}{\beta_1 \ldots \beta_n} d^2 r_1 \ldots d^2 r_n \Psi_n^*(\beta_1, \ldots, \beta_n, \vec{R}_1, \ldots, \vec{R}_n) \times \Psi_n(\beta_1, \ldots, \beta_n; \vec{R}_1, \ldots, \vec{R}_n) = 1. \tag{1.12}$$

The above-formulated hypothesis about the finiteness of $r_i = p_{i\perp}$ and, in general, of the momenta of the internal motion has led us to the fact that the wave function depends on the ratio of the momenta β alone. Thus, this implies the scale invariance of the matrix elements.

The Fock column which is composed out of the functions (1.10) is a wave function of the parton model[6]. Owing to the property of the interaction Hamiltonian to vanish at $P_z \to \infty$ which we have postulated, this function describes the mixture of practically noninteracting particles-partons. The parton model is a natural relativistic generalization of the impulse approximation.

In particular, it is not difficult to show (see ref. [5]) that the matrix element of the bilinear scalar density between the two states of a hadron composed of the two constituents is proportional to the integral

$$\int\Psi^*(\beta_1, R_1^2)\,\Psi[\beta_1, (\vec{R}_1+\beta_1\vec{Q})^2]\,\frac{d\beta_1}{\beta_1(1-\beta_1)^2}\,d^2R, \tag{1.13}$$

where $\vec{Q}=\vec{r}-\vec{r}\,'$ is the transverse momentum of an external effect.

This formula has a simple nonrelativistic analog in the impulse approximation. In the initial state we have a hadron in a frame with zero transverse momentum; $\Psi(\beta_1, R_1^2)$ is the amplitude for a two-parton state with parton 1, having momentum $(\beta_1, \vec{R}_1)$ and parton 2 having momentum $[(1-\beta_1), -\vec{R}_1]$. Then a transverse momentum Q is deposited on parton 2 to bring its momentum to $[(1-\beta_1), -\vec{R}_1+\vec{Q}]$. The hadron has a center of mass velocity in the transverse plane given by Q. Thus to project the state onto the final hadronic state we must transform the wave function of the final hadron by a transformation of (1.8) type to a frame in which it moves with velocity Q. This takes each transverse momentum and translates it by amount βQ so that the argument of the final state function is $(\vec{R}_1+\beta_1\vec{Q})^2$.

This apparatus gives only a recipe for overcoming the troubles of relativistic description but does not answer the question as to how to construct the wave functions of the type (1.10). However, this apparatus can be used to express the cross section of any process in terms of the cross section (σ_b^f) of interaction with parton b and the universal distribution of the parton number $D_{B/b}(\beta, R^2)$ by means of the following formula

$$\sigma_B^f(\beta, R^2) = \sum_b \int \frac{d\beta'}{\beta'}\,\sigma_b^f\!\left(\frac{\beta}{\beta'}\right) D_{B/b}(\beta', R^2)\,. \tag{1.14}$$

Here $D_{B/b}$ is the probability for finding a parton (quark) of sort b in a hadron, e.g., nucleus, B with momentum fraction β and any transverse momentum R. The summation is performed over all the quantum numbers of the parton (spin, color, flavour).

For the lepton-hadron scattering

$$\ell + h \to \ell' + X$$

we have $\sigma_b^f=\sigma_0^b\cdot\delta(1-\frac{\beta}{\beta'})$ the cross section of scattering of a lepton on a point-like parton and then find

$$\sigma_h(\beta, R^2) = \sum_b \sigma_0^b\cdot D_{h/b}(\beta, R^2)\,. \tag{1.15}$$

The analysis of the experimental data on the inclusive scattering of leptons on hadrons on the basis of eq. (1.15) has been of an exceptional importance in the present-day theory which made it possible to prove not only the validity of the parton model, but also the fact that the partons are quarks. The

point-like character of the parton-quarks means that the effective coupling constant of the quarks with gluons is small and decreases with increasing momentum transfers in virtue of the quark asymptotic freedom. The quantum chromodynamics (QCD) has enabled one to give grounds for the parton model as a reasonable first approximation and to calculate scale invariance violation corrections. However, the existing theory does not permit to calculate explicitly $D_{B/b}(\beta)$'s and these are experimentally determined quantities. The study of similar functions for large momentum transfers to nuclei is one of the basic problems of the relativistic nuclear physics.

II. LARGE MOMENTUM TRANSFERS TO NUCLEI

In the analysis of experimental data in hadron physics invariant inclusive cross sections (one-, two- and so on particle distributions)

$$\rho_1 = \frac{E}{\sigma_{in}}\frac{d\sigma}{d\vec{p}}\,;\quad \rho_2 = \frac{E_1E_2}{\sigma_{in}}\frac{d\sigma}{d\vec{p}_1\,d\vec{p}_2}\ \text{and so on,} \tag{1.16}$$

which correspond to the fixation in the final state of one-, two- and so on particles

$$\begin{aligned} &I + II \to 1 + X,\\ &I + II \to 1 + 2 + X, \end{aligned} \tag{1.17}$$

are used as measurable quantities. Here ρ_1, ρ_2 and so on depend on relativistic invariants and, in particular, on $s=(p_I+p_{II})^2$; σ_{in} is the inelastic cross section for reactions proceeding in the collision of systems I and II.

The study of the limiting fragmentation suggested by Yang et al. /7/ $s=(p_I+p_{II})^2\to\infty$ was found to be very useful. This limit corresponds to scale invariance of the cross sections. They are shown to depend only on the ratio of the momenta of newly produced and incident particles.

This idea is very simply expressed in terms of the so-called short-range correlations (SRC) in the rapidity space which are introduced instead of the above-mentioned variables β_i. By the rapidity we mean the quantity

$$y = \frac{1}{2}\ln\frac{E+P_z}{E-P_z} = \operatorname{arsh}\frac{P_z}{\mu}\,;\quad \beta_i = \frac{E_i+p_{iz}}{E_I+P_I} = \frac{\mu}{m_I}e^{y_i-y_I}\,, \tag{1.18}$$

where $\mu_i=\sqrt{r^2+m^2}$. For nonrelativistic energies $y \simeq v_z$.

We notice the most important property of the rapidity: for the Lorentz transformation along the z axis this variable changes in an additive manner. Correspondingly, the rapidity difference remains invariant in just the same way as β. Owing to the properties mentioned the distributions ρ depend on the rapidity differences (the $\vec{r}^{\,2}$ dependence is, for the moment, omitted)

$$\rho_1(y_1 - y_I\,;\, y_I - y_{II}),$$
$$\rho_2(y_1 - y_I\,;\, y_1 - y_2\,;\, y_2 - y_{II})\,. \tag{1.19}$$

For definiteness we assume the rapidities to be ordered as

$$y_{II} < y_2 < y_I < y_1\,. \tag{1.20}$$

SRC is determined from the following conditions:

1. If the rapidity differences are much larger than the characteristic correlation length $L \approx 2$, then ρ_m is independent of this variable, in particular, of $(y_I - y_{II})$ which corresponds to the limiting fragmentation.
2. If $y_1 - y_2 > L$, then ρ_2 is factorized to a product of one-particle distributions

$$\rho_2(y_1 - y_I\,; y_1 - y_2\,;\, y_2 - y_{II})\big|_{y_1 - y_2 > L} \to \rho_1(y_1 - y_I)\cdot\rho_1(y_2 - y_{II})\,. \tag{1.21}$$

These conditions are generalized to any ρ_m, where $m \geq 3$, in a trivial manner.

A priori there is no special reason to believe that there exists a universal correlation length L which is valid for all types of high-energy reactions. Moreover, strictly speaking, the correlations should not be only of short-range order, at least, because of the restrictions imposed by energy-momentum conservation. Nevertheless, the short-range correlation model well describes many characteristics of multiple particle production and may be viewed as an approximate universal property of hadron interactions [8].

Nuclear collisions should obey the laws discovered in hadron physics and, in particular, the use of short-range correlations is found to be especially efficient in relativistic nuclear physics.

Fistly, this model enables us to predict the region of approximate validity of limiting fragmentation. Recall

$$(p_I \cdot p_{II}) = m_I m_{II}\, \mathrm{ch}(y_I - y_{II}) \approx m_I m_{II} \frac{1}{2} \exp|y_I - y_{II}|\,.$$

The case $|y_I - y_{II}| \geq 2$ corresponds to this approximate boundary, or

$$(p_I \cdot p_{II}) = E_I m_{II} \approx m_I m_{II} \frac{1}{2} \exp|y_I - y_{II}| \gtrsim m_I m_{II} \frac{1}{2} \exp 2$$

or: $2\frac{E_I}{m_I} \gtrsim e^2 \approx 7.4$, i.e., at an energy E_I of about 4 GeV/nucleon. This boundary appears to be in agreement with the condition (1.1): $\frac{p_I^2}{m_I^2} \approx 14 \gg 1$.

If the rapidity difference $(y_I - y_{II})$ obeys the condition

$$(y_I - y_{II}) > L \approx 2, \tag{1.22}$$

then the cross section is factorized. The happening near the left boundary (y_{II}) does not affect the vicinity of the right boundary (y_I), and vice versa. In particular, it follows from here that for the study of the limiting fragmentation of heavy nuclei there is no necessity to accelerate them. It is enough to study the production of particles with large momentum transfers on heavy nuclei under the action of any particles of sufficiently high energies so that the condition (1.22) should be fulfilled. The cross sections obtained in such a way can be transformed in a coordinate frame, where the heavy nucleus is moving, and secondary beams, which will be obtained, for example, from uranium acceleration, can be predicted.

It is just this statement of the problem that has been used to study the main regularities of the limiting fragmentation of nuclei at Dubna starting with 1971. We focuse our attention on the one-particle distributions in the region of limiting fragmentation of nuclei which is kinematically forbidden for one-nucleon collisions. In the region $\exp|y_I - y_{II}| \gg 1$, from the energy-momentum conservation it follows

$$\mu_1 \exp(y_1 - y_I) \lesssim m_I\,. \tag{1.24}$$

We determine the kinematic limits with the aid of the cumulative number N, i.e., the effective number of the nucleons of a fragmenting nucleus which are involved in the reaction. For the one-particle distributions the minimal N^{min} is determined by the kinematic limits imposed on the mass of the object participating in the collision

$$I + II \to 1 + X\,.$$

When $\exp|y_I - y_{II}| \gg 1$ in the region of limiting fragmentation of nucleus 1 the relativistic invariant quantity N^{min} assumes, according to eq. (1.24), the following values

$$N^{min} = \frac{\mu_1 \exp(y_1 - y_I)}{m_p} = \begin{cases} \dfrac{E_1 - p_{1z}}{m} & \text{in the rest system of nucleus I} \\[2ex] \dfrac{E_1 + p_{1z}}{E_I^{\circ} + p_I^{\circ}} & \text{in the rest system of particle or nucleus II,} \end{cases} \tag{1.25}$$

where p_I° is the momentum per nucleon; m_p, the proton mass; y, the rapidities; p_{Iz}, the longitudinal momentum. The cumulative effect corresponds to the region defined as $N^{min} > 1$.

The cumulative effect was predicted [1] on the basis of the following assumptions. In the spirit of the parton models the one-particle distribution ρ_I in the region of the limiting fragmentation of nucleus I is taken in the form of a superposition of the one-particle distributions which are due to the limiting fragmentation of the objects of mass $N \cdot m_p$ inside nucleus I

$$\rho_I^{II}(y_1 - y_I, \vec{r}_1) = \sum_N P_N \rho_N (y_1 - y_I, \vec{r}_1) . \qquad (1.26)$$

Without further assumptions on the probability P_N for finding a constituent with mass Nm_p inside the nucleus and on an explicit form of ρ_N the following properties of the cumulative effect can be obtained:

1. The dependence of ρ_I^{II} on the properties of the target (particle II) must practically be absent due to limiting fragmentation.

2. We introduce in eq. (1.26) instead of the rapidity difference the quantity N^{min} according to eq. (1.25) and rewrite eq. (1.26) in the form

$$\rho_I^{II}(N^{min}, \vec{r}) = \sum_N P_N \rho_N (N^{min}, \vec{r}) . \qquad (1.27)$$

According to the definition of ρ_N and eq. (1.25)

$$\rho_N (N^{min}, \vec{r}_1) = 0 \quad \text{for} \quad N < N^{min} .$$

It is then clear that N^{min} defines the lower limit of summation (or integration if N is continuous). It is doubtful whether one can expect that many nucleons can get together in the cumulation volume. Consequently, P_N is a sharply decreasing function of N and it may be supposed that

$$\rho_I^{II}(N^{min}, \vec{r}_1) \approx P_{N^{min}} \cdot \rho_{N^{min}} (N^{min}, \vec{r}_1) . \qquad (1.28)$$

Thus, according to our model the main quantity which describes the cumulative effect ρ_I^{II} can be approximated by a fast decreasing function, e.g., exponential

$$\rho \approx C \exp[-aN^{min}] , \qquad (1.29)$$

where a and C are practically independent of the properties of particle II in the region of the limiting fragmentation of nucleus I. Eq. (1.29) well describes the experimentally observed distributions of the cumulative particles over the variable N^{min}, which, according to eq. (1.18), coincides with the β variable discussed in Section I. However, in Section I we discussed the parton (quark) distribution, and here we are discussing the particle distribution. The short-range correlations in the rapidity space for particles produced at large momentum transfers correspond to those in the rapidity space for partons. Hence, it follows that the cumulative hadron can be produced only of the cumulative parton. Owing to this property the distributions of cumulative particles coincide with those of cumulative partons. The production of hadron jets in the high-energy particle interaction is one of the important predictions of the parton model. According to the parton picture, the distribution of the most rapid hadrons in a jet must be about the same compared with that of the most rapid partons differing from the former by a shift of the order $\Delta y \sim 1$. This fundamental property was given grounds in quantum chromodynamics and is a reflection of the asymptotic freedom of quarks. It was given the name of soft hadronization or soft color neutralization. Hence it follows that the spectra (1.29) reflect the distribution of partons (quarks) in nuclei, in other words, $D_{B/b}(\beta)$.

3. Simple geometric considerations have led us (see, e.g., ref. [8]) to the following dependence of the coefficient C in eq. (1.29) and, consequently, $D_{B/b}(\beta)$ on the fragmentation nucleus atomic weight: $C \propto A^{N^{min}/3}$. Such type dependences were found to be rather nontrivial so that a number of experimental studies has been devoted to them. For large N^{min} the exponent m in the dependence $\sigma \propto A^m$ is larger than unity.

It should be noted that according to QCD the distribution $D_{B/b}(\beta)$ describes not only the probability of production of a parton b in a hadron B but also the probability, $\bar{D}_{b/B}(\beta)$, of the inverse process, that is, hadronization of a parton (quark) b to a hadron B. But $D_{B/b} \propto A^{N^{min}/3}$ from where it follows that the A dependence of the production cross section for heavy (multiquark) cumulative particles will strongly increase. The latter fact is explained by that the pickup probability for additional quarks and whole nucleons increases with increasing thickness ℓ of the matter lying on the way of the cumulative parton ($\ell \sim A^{1/3}$). We employ this fact (see ref. [9]) to explain the following experimental regularities of the limiting fragmentation of the nucleus into various cumulative particles

$\sigma(A \to \pi) \propto A$

$\sigma(A \to p) \propto A^{4/3}$

$\sigma(A \to d) \propto A^{5/3}$

$\sigma(A \to t) \propto A^{6/3}$

and predict further increase of the A dependence in the transition to heavier cumulative particles in an approximate correspondence with the A^B law, where B is the cumulative particle baryon number.

The predicted properties of the cumulative effect have well been confirmed experimentally. The observed energy dependences of the production cross section for cumulative particles are described by simple exponentials. It is interesting to note that the simplest dependence (1.29) describes in an approximate manner all the regularities of the cumulative particle production, including the angular distributions. The main properties of the cumulative meson production were discovered in 1971 and are being studied by Stavinsky's group at Dubna [10]. The limiting fragmentation of nuclei from deuterium to uranium was investigated in the range of the cumulative number up to 4. As the cumulative particles pions, protons and nuclear fragments were studied. A detailed description of the presently known properties of the cumulative effect is given in the talk by Stavinsky submitted to the present Conference. Here I would like only to stress and illustrate three very important facts:

1. Following the above-presented theoretical ideas the universal function (1.29) which describes all the spectra of cumulative particles (π, K, p, Λ, d, t, ^{4}He) is a quark-parton distribution $D_{B/b}(\beta)$ in the region $N = \beta A > 1$. It can be used for the prediction of the results of other experiments, e.g., the results of deep inelastic scattering

$$\mu + {}^{12}C \to \mu + X, \tag{1.30}$$

which is being studied at CERN on the NA-4 installation created with the participation of Dubna physicists. With the aid of this installation it is supposed both to study certain regularities of QCD and measure the neutral current parameters. It is very important for all these effects to obtain as large as possible momentum transfers Q^2. It is for just these reasons that the giant NA-4 installation has been created. Up to the present time these effects were studied in the region of the one-nucleon variable $\beta_N \approx x = \frac{Q^2}{Q^2_{max}} < 1$, where Q_{max} is defined by the incident μ meson energy.

To this end, we suggest to use the cumulative effect, i.e., to study the process (1.30) in the region $A\beta = \beta_N \approx x > 1$. According to eq. (1.29) the quark-parton distributions in this region decreases rapidly in an exponential manner. However, Stavinsky's group has succeeded in measuring these distributions to $N^{min} = \beta_N \approx x > 3$. If the luminocities of the NA-4 installation will be found to be enough for measuring the cross sections of the process (1.30) in the region $x \geq 3$, then the reached Q^2 would correspond to the possibilities of an accelerator at an energy higher than 1000 GeV for the usually used region $\beta_N \approx x < 1$.

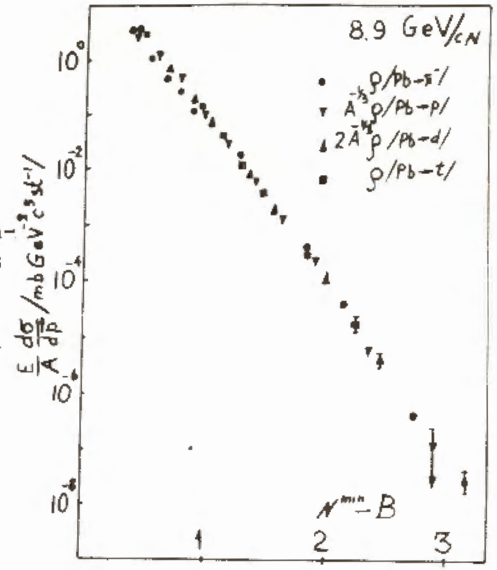

Fig.1

The universality of the function (1.29) is best illustrated by Fig.1, where this dependence is measured for the change of the cumulative particle production cross section by nine orders of magnitude. The universal character of this function for various cumulative particles including light nuclei, shows that the "soft character" is assigned not only to the quark hadronization, but also to the nucleon pickup in the formation of composite baryon systems. These processes appear to have much in common.

2. As we repeatedly emphasized [11,12] the limiting nuclear fragmentation begins in the region $|y_I - y_{II}| \approx L \approx 2$, i.e., at an energy per nucleon 3.5-4 GeV. In other words, for nuclear collisions at an energy per nucleon $E_I^\circ \gtrsim 4$ GeV/c the quantities C and a in eq. (1.29) cease to depend on E_I° and reach asymptotic values. This conclusion is a matter of principle because it establishes the values of the momentum transfers at which the quark degrees of freedom begin playing the important part. The universality of the smooth plot (1.29) shows that in the cumulative region the nucleon as a quasiparticle of nuclear matter is not adequate to the problem. In this region the quark components of different nucleons are strongly mixed. The departure of the quantity a on the asymptotic regime has recently been confirmed by American physicists whose

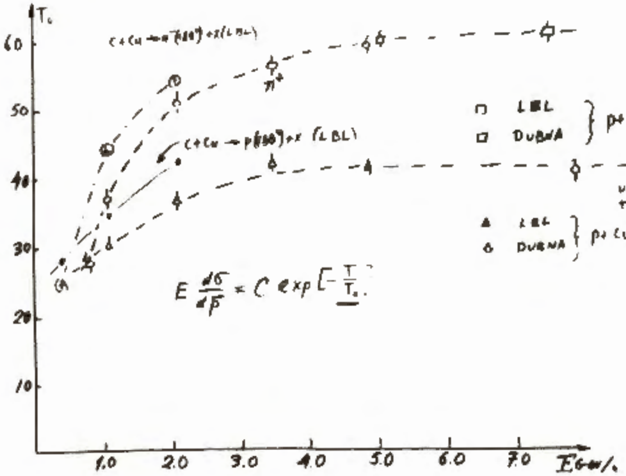

Fig.2

result is illustrated in Fig.2 taken from the review by Scott at the Erice School in 1979. The quantity T_0^{π} is seen to be $\frac{m_p}{2a}$ and the energy per nucleon E_I° is plotted on the absciss axis. There is a rather satisfactory agreement between the LBL and Dubna data. It is also important to point to an agreement with the data of the Soviet-American collaboration obtained at $E_I^{\circ} = 400$ GeV/N (the last point on the right).

3. A special attention should be paid to the study of the polarization phenomena in the cumulative effect and the dependence of the cumulative effect cross section on the quantum numbers (flavours). In ref.[13] a polarization of Λ hyperons has been observed in the reaction $\pi^- + A \to \Lambda + X$ for $p_\pi = 2.9$ GeV/c where as the target a mixture of the carbon and xenon nuclei is used. Further increase of the appropriate statistics [14,15] has little changed the result. The presence of large polarization in deep inelastic processes was found to be very surprising, although as early as in 1967 Leskin's group obtained [16] an indication to a possible large polarization of protons scattered with a momentum transfer lying outsides the limits of one-nucleon kinematics. Experiments of ref.[17] have confirmed the large value of the cumulative Λ particle polarization. All the polarization measurements are provided with little statistics. However, the data of all the four papers are in good agreement with one another. The presence of large polarization in the cumulative effect has been explained in the model of hard collisions by Efremov [18]. It is possible that

the polarization studies in hard collisions will turn out to be a very critical check of QCD since in this theory the polarization results only from the account of the highest approximations of perturbation theory, at least, of two-gluon exchanges. However, for the time being, it is very hard to take into account the highest approximations in a quantitative manner.

An effective study of polarization phenomena in the cumulative effect can be performed with the aid of intense beams of relativistic polarized deuterons the work on the obtaining of which is being performed at the Laboratory of High Energy Physics of the Joint Institute for Nuclear Research. More reliable information about quark-parton distributions in nuclei is extracted from the study of cumulative jets rather than from the study of cumulative particles. By the cumulative jets we mean the distribution of groups of particles flying into the backward hemi-sphere over the resulting cumulative number $\beta_s = \sum_i \beta_i$. Contrary to the jet, the production of one cumulative particle proceeds with the participation of only a fraction of the momentum of the initial parton.

I do not intend to give here a detailed review of theoretical studies devoted to the analysis of the cumulative effect and other manifestations of the quark degrees of freedom in nuclei. This aspect is discussed in the talks submitted to the present Conference by Matveev and Lukianov. Review papers [19a-g] may also be recommended. A more detailed consideration of the related problems is presented in my lectures at the Erice School (1979) [9].

III. PRESENT STATUS AND PERSPECTIVES OF STUDIES IN THE FIELD OF THE RELATIVISTIC NUCLEAR PHYSICS AT THE JOINT INSTITUTE FOR NUCLEAR RESEARCH

For the nearest years the main tools of the relativistic nuclear physics will be the proton synchrotron and detectors of the elementary particle physics. The intensity of the extracted nuclear beams is already now much higher than the intensity of the beams of secondary particles (pions, kaons, etc.) which the existing detectors are rated at. The secondary beams, even pion ones, with an intensity $10^5 - 10^6$ part./sec are considered to be good for the available facilities and the extracted beams of relativistic nuclei have an intensity of $10^6 - 10^{11}$ part./sec. This provides us with an encouraging perspective of applying the existing detectors created for the work with secondary beams in the relativistic nuclear physics.

The relativistic nuclear beams the parameters of which will be improved undoubtedly in the nearest future and the available detectors will make it possible to resolve many of the problems discussed.

Five electronic installations and three track detectors: liquid hydrogen bubble chamber, two-meter propane bubble chamber and two-meter streamer chamber on the Dubna synchrophasotron are used for studies in the field of relativistic nuclear physics. For the exception of the Stavinsky group's installation which was used to obtain the main results on the cumulative effect, all these facilities were intended for performing studies in the field of particle physics, and it is only lately that they have been adjusted for investigations with relativistic nuclei.

In the first installation of Stavinsky's group specially created for studying processes of the type $p + A \to \pi(180^\circ)$ pions were detected by a DISC-type Čerenkov differential counter with a velocity resolution $\Delta\beta = \pm 3{\cdot}10^{-2}$ in a velocity range 0.7÷1.0. The second version of this installation is a rotating magnetic spectrometer which allowed to perform detailed measurements of the angular cumulative particle distributions. Events were there extracted by an independent measurement of the time of flight on two bases (4 and 1 meter) with an accuracy 150÷200 psec and measurement of ionization losses and intensity of the Čerenkov burst in a solid radiator. The description of these facilities is given in refs. /20,21/. A review of the recent results of Stavinsky's group is presented in his talk submitted to this Conference.

The study of the nucleus-nucleus scattering at small transfers is performed on the internal accelerator targets. This technique /22/ which was developed on the Dubna synchrophasotron with the participation of the same physicists started the well-known investigations with the aid of a supersonic jet target on the Serpukhov and Batavia accelerators. Recently the method of thin internal targets has been applied on the synchrophasotron for measuring the cross sections of nuclear collisions with large transverse momenta. Fig.3 illustrates the data obtained.*

The one-arm magnetic spectrometers with proportional chambers are used for measuring the inclusive cross sections for relativistic nuclear collisions /23,24/. An installation "Photon" is oriented to studying relativistic nuclear collisions with emission of neutral particles ($\pi^\circ, \eta^\circ, \omega^\circ$). It is a 90 channel Čerenkov hodoscope of lead glass in which the gamma quantum energy is measured. The direction of gamma quanta is measured by 32 spark chambers with a magnetostrictive readout. The accuracy of measurement of the gamma quanta direction depends on the thickness of the converters and amounts to 3.4 mrad. A large complex of electronic apparatus and an on-line computer of the installation "Photon" make it possible to study effectively multiple photon emission in relativistic nuclear collisions, in particular, the problem formulated in ref. /25/ on cumulative production of vector mesons.

*The author is grateful to V.A.Nikitin who has acquainted him with these data.

Among track devices the 2-meter propane chamber has been advanced most greatly for the purposes of relativistic nuclear physics. The multiple particle production in relativistic nuclear collisions is found to be simpler from the topological viewpoint than that in p-p collisions at an energy of hundreds of GeV. A large group of physicists under the leadership of Soloviev has solved the principal problems of handling of such photographs and has obtained a large amount of experimental information on multiple production processes of relativistic nuclear physics. A talk of Soloviev devoted to this problem is submitted to the present Conference. A review of earlier results was given by Bartke at the 8th International Conference on High Energy Physics and Nuclear Structure (Vancouver, 1979).

Of a particular interest are the search for and study of multibaryon resonances the existence of which is predicted by

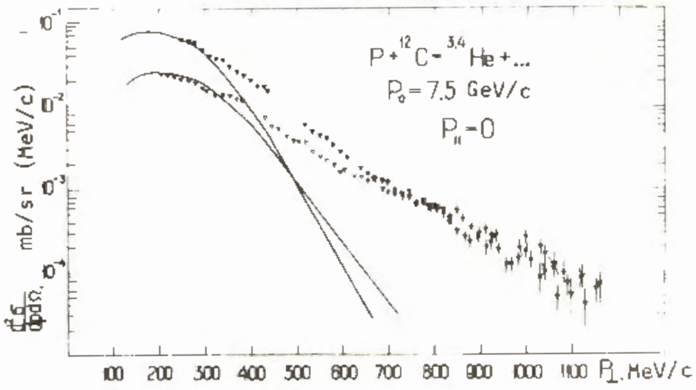

Fig.3

the quark bag theory. The (Λp) and, possibly, ($\Lambda\Lambda$) and ($\Lambda\Lambda p$) resonances discovered by Shakhbasian on the basis of the study of photographs from the propane bubble chamber were lately interpreted [26,27] as multiquark formations in a single "bag". The confirmation of the existence of such large "quark plasmons" would be very important, in particular, it would mean that we have already discovered metastable states of superdense nuclear metter, i.e., multibaryon states possessing elementary particle density. In the same experiments it is found to be possible to study the cumulative production of Λ particles, including the study of their polarization (see above). The relationship between the cumulative effect and the manifestation of quark plasmons is one of the most interesting and important objects of the investigations in relativistic nuclear physics.

Figure 4 presents a photograph of the interaction of the ^{20}Ne nucleus with a momentum 90 GeV/c with the ^{20}Ne nucleus in the 2-meter streamer chamber. The description of this apparatus is given in ref. [28]. This chamber was used to show the analogy of the multiplicity distributions of negative particles in nucleus-nucleus collisions and in p-p collisions at high energies.

For the study of exclusive reactions in relativistic nuclear physics use is made of a 1-meter liquid hydrogen chamber. It is bombarded by ^3He and ^4He nuclei (see, e.g., ref. [34]). The same bubble chamber has been used for the study of the n+p reactions with monochromatic neutrons of a variable energy which was a primary aim of the deuteron acceleration on the synchrophasotron in 1970.

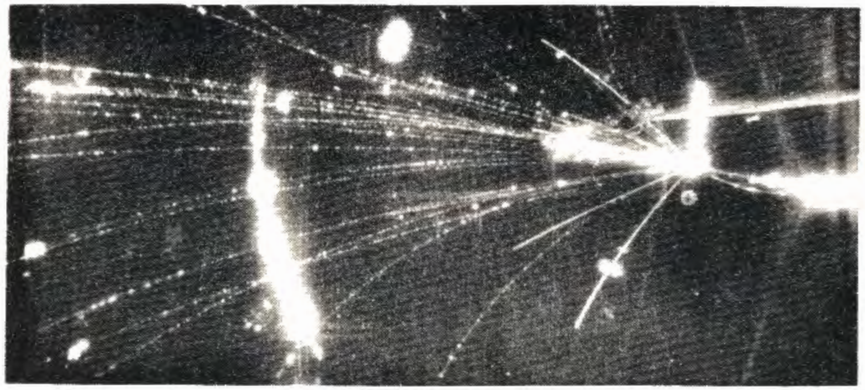

Fig.4

The first experiments on deuteron acceleration on the Dubna synchrophasotron in 1970 showed that in order to proceed to the acceleration of nuclei with the aid of ordinary proton accelerators the accelerating system needs not be strongly modified. Thus, any high energy accelerator can be adapted to accelerate deuterons and α particles.

In order to pass to the acceleration of nuclei with large atomic masses a number of technological problems should be resolved. The main of them is the obtaining of bare nuclei. The acceleration of partially ionized atoms imposes very strict requirements on the vacuum inside the accelerator chamber. To obtain bare nuclei it is suggested to create pre-accelerators with an intermediate stripping.

Following the recommendation of G.N.Flerov, our Laboratory has engaged in developing essentially new sources of heavy ions: electron beam ion and laser sources. The electron beam ion source invented by Donetz is a rather compact device which has reliably been running on our synchrophasotron for a long time under operating conditions. The principle of operation of the source consists in the following. A certain amount of one-charged ions of an element to be accelerated is introduced into an electron beam of high density (hundreds of amperes per cm^2). The ions perform radial oscillations under the action of the forces of the electric field of the electron space charge. The interaction of the ions with the fast electrons of the beam produces a multiple ionization; the ion charge increases. The electron beam is placed in a deep vacuum in a strong longitudinal magnetic field (superconducting solenoid). Cryogenics makes it possible to obtain a magnetic field of practically any necessary value and reach a vacuum in an ionization region of 10^{-11} torr. This sourve is sometimes called "CREBIS" (cryogenic electron beam ion source). The present status of the relative investigations enables us to hope to obtain bare nuclei of an intensity of about $10^{11} \cdot 1/Z$.

In 1980-1982 an increase of the intensities of ^{12}C, ^{14}N, ^{16}O and ^{20}Ne is expected to be at the expense of an improvement of the injection system, but this increase will not be larger than by a factor of 10^2. An essential expansion of the beam facilities will take place after the creation of a synchrophasotron buster.

Relativistic acceleration of heavy nuclei and even intermediate mass nuclei requires creation of special injection complexes, pre-accelerators at an energy about 500 MeV/N, which are of a great value by itself. The high voltage injection resolves also vacuum problems in the main ring since

The beam intensities of the Dubna synchrophasotron

Accelerated particles	Energy in GeV per nucleon	Particle intensity per pulse
protons	10	$4\cdot10^{12}$
deuterons	5	$5\cdot10^{11}$
^{4}He	5	$3\cdot10^{10}$
^{12}C	5	$2\cdot10^{6}$
^{14}N, ^{16}O	5	10^{4}
^{20}Ne	5	sufficient for experiments to be performed in the streamer chamber

for ions of an energy higher than 500 MeV/N the electron pick-up is nonessential even for rather moderate requirements on the vacuum.

Thus, the following research programme is worked out at the Laboratory of High Energy Physics of the JINR. During the nearest 4-5 years it is planned to use extensively the beams of relativistic nuclei of the synchrophasotron up to 5 GeV/N energies. As we have already stressed, the limiting fragmentation of nuclei begins at an ion energy higher than 3 GeV/N. This ion energy range has, as yet, been obtained in no other accelerator centers. The available detectors will make it possible to realize a rather wide programme of investigations. By the present time it has been completed the construction of a large experimental hall of an area of about 10^4 m^2 in which a large number of simultaneously operating installations can be arranged on the extracted beams of the synchrophasotron.

Further perspectives of our Laboratory are connected with the creation of a superconducting specialized accelerator of nuclei which will replace the synchrophasotron. Some progress has also been made in the creation of superconducting magnets for accelerators (see, e.g., ref. [29]). At the Laboratory there are some advances in the creation of superconducting magnets with an iron-shaped magnetic field (see, e.g., ref. [29]). Though the magnetic field is restricted by a value of 2.5 T, the construction of the magnet becomes, in turn, essentially simpler, the winding volume and the weight of the magnetic circuit decreases which essentially facilitates their manufacture in the lab. conditions.

The small superconductor volume and the low value of the energy stored in the winding enable us to hope to reach high frequencies of repetition of acceleration cycles (0.1-0.5 H_Z) and a growth of the average beam intensity. A group of engineers and physicists of the Laboratory of High Energy Physics under the leadership of Shelaev has got good dipole and quadrupole parameters.

Some preliminary suggestions concerning the design of a superconducting accelerator of relativistic nuclei which was given the name "Nuclotron" are presented in refs. [30,31]. They have underlain projects of construction of an injection complex of the Laboratory of High Energy Physics and, in particular, its intermediate ring accelerator the main parameters and the operating regime of which are given in ref. [32]. The creation of the Nuclotron on the basis of the resources available at the Laboratory (buildings, tunnel, energetics, large experimental hall equipped with a system of channels, detectors, etc.) will make it possible to lower noticeably the cost of the accelerator complex.

The first stage of construction of the Nuclotron is the creation of a buster of an energy of few hundreds of MeV/N. The use of it as a synchrophasotron injector at this stage will essentially improve the JINR beam facilities. The buster beams will also be applied to studies of supersonic and high-temperature nuclear reactions, as well as to medical and space research, etc.

The creation of the intermediate ring accelerator-buster has attracted the attention of physicists of the Kurchatov Institute. They proposed an interesting research programme in the energy range up to 0.5 GeV/N (see the talks of Galitzky and Ogloblin submitted to the present Conference).

Efforts of both the institutes were combined and the initial design of the intermediate accelerator [32] underwent some changes [33]. Other institutes of the JINR member-countries have expressed their interest in supporting the creation and development of the heavy-ion acceleration complex.

Thus, the Laboratory of High Energy Physics research programme implies constant development of the accelerator complex with actually unceasing and intense use of relativistic nuclear beams. This provides us with large possibilities of performing investigation in the new and very perspective field of physics, the relativistic nuclear physics.

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