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исследований
дубна

E1-87-829

L.A.Didenko, V.G.Grishin, A.A.Kuznetsov

SEARCH FOR AND STUDY OF THE ASYMPTOTIC PROPERTIES OF HIGHLY EXCITED NUCLEAR MATTER

Submitted to XVIII International Symposium on Multiparticle Dynamics, Tashkent, 1987

1987

1. INTRODUCTION

The asymptotic properties of highly excited nuclear matter (nucleon and hadron) have been studied by analysing the general characteristics of baryon clusters and hadron jets (respectively) produced in different hadron and nuclear interactions over an energy range from 4 to 205 GeV using a new relativistic invariant approach to the description of these processes.

Multiple particle production is the main process of relativistic nuclear physics.

In distinction to traditional approaches (e.g., inclusive, semi-inclusive and so on) to the description of multiple particle production, the method employed by us makes it possible not only to more completely use experimental information but also to order a complicated picture of relativistic nuclear processes and to distinctly classify nuclear interactions.

In the invariant method of analysing [1] multiple particle production, the processes

$$I + II \to 1 + 2 + 3 + \ldots \tag{1}$$

are considered in a space the points of which are the 4-velocities $u_i = P_i/m_i$ or the 4-momenta P_i divided by the masses m_i.

The positive invariant quantities having the meaning of the squared distance in this space

$$b_{ik} = -(u_i - u_k)^2 = 2[(u_i u_k) - 1], \tag{2}$$

where i,k = I,II,1,2,3,...,are basic variables describing the relative particle motion.

The idea [2] of introducing the b_{ik} variables consists in that a statistical regularity is realized in the cross sections of processes (1): in definite domains of the b_{ik} variables the b_{ik} distributions decrease monotonously and rather rapidly with increasing b_{ik} by analogy with a decrease of the interaction between objects i and k with increasing their relative velocity ($b_{ik} \to \infty$). The existence of the asymptotic behaviour of the cross sections as a function of b_{ik} results from the generalization of experimental observations, and it can underly the formulation of the common properties of the cross sections of hadron and nuclear interactions, the correlation depletion principle (CDP)[3], in the relative velocity space by analogy with Bogolubov's principle in statistical mechanics and the automodelity principle in mechanics of continua.

The b_{ik} variables and the probability distributions (cross sections) depending on them are really measured quantities:

$$W(\ldots, b_{ik} \ldots) = \frac{d\sigma}{\prod d b_{ik}} . \tag{3}$$

It is evident that the knowledge of all b_{ik} for all particles of a type (1) process contains full information on this process.

If the set of these experimentally determined quantities is separated into two groups

$$\{\ldots, b_{ik}, \ldots\}^{\alpha} \qquad \text{and } \{\ldots, b_{jn}, \ldots\}^{\beta},$$

the CDP leads to that in the asymptotic limit, when the b_{ik} distances (intervals) between points i and k from different groups tend to infinity, the probability distributions $W^{\alpha\beta}$ decay into factors. One of the factors describes the particles from the group α and another from the group β, i.e.

$$W^{\alpha\beta}\big|_{b_{\alpha\beta} \to \infty} \to W^{\alpha\beta} \cdot W^{\beta} . \tag{4}$$

In other words, the distributions, describing multiple particle processes, are factorized in the 4-velocity space b_{ik}, i.e. they decay into factors relating to different clusters in this space.

The automodelity principle using the $b_{\alpha\beta}$ variables that assume asymptotically large values can be formulated[4] as the so-called intermediate asymptotics:

$$W(b_{\alpha\beta}, b_{\alpha k}, b_{\beta k}, b_{ik}, \ldots) \to \frac{1}{b^m_{\alpha\beta}} W(b_{\alpha k}, \frac{b_{\beta k}}{b^m_{\alpha\beta}}, b_{ik}, \ldots). \tag{5}$$

where the parameter m, characterizing the velocity of tending W to zero, is found experimentally or predicted theoretically.

Joining the CDP and the automodelity principle, the probability distributions $W^{\alpha\beta}$ can be presented as

$$W^{\alpha\beta} \simeq W^{\alpha} \frac{1}{b^m_{\alpha\beta}} W^{\beta}, \tag{6}$$

where W^{α} and W^{β}, independent of large $b_{ik} \sim b_{\alpha\beta}$, depend only on their ratio in the asymptotic limit. According to[2], in our case the ratio of large quantities $(b_{\beta k} / b_{\alpha\beta})$ having a finite value at $b_{\alpha\beta} \to \infty$ can be written as follows:

$$\left(\frac{b_{\beta k}}{b_{\alpha\beta}}\right) \to \frac{(u_\beta u_k)}{(u_\beta u_\alpha)}\Big|_{\vec{u}_\alpha = 0} = \frac{u_{\beta 0} u_{k0} - (\vec{u}_\beta \vec{u}_k)}{u_{\beta 0}} \to x_k = u_{k0} - u_{kz} . \tag{7}$$

Here x is the light front variable of particle k and the Z axis is directed along the line connecting the vectors of the average velocity of particles in the α and β groups. According to their definition, W^{α} and W^{β} describe the systems of particles (isolated systems) which are independent of one another. Let V_α be an average point of the system (group) of strongly interacting particles, u_k the velocity of a k-th particle belonging to the system and u_i the velocity of an i-th particle not belonging to the system. The system is called "isolated" if all $b_{\alpha i}$ for all particles belonging to the system W^{α} are much smaller than $b_{\alpha k}$ for all particles which do not belong to the system:

$$b_{\alpha k} \gg b_{\alpha i} \sim b_0 ,$$

where b_0 is a characteristic correlation length. According to the CDP, interactions and correlations between the particles belonging to the system and those not belonging to it are negligibly small.

It should be stressed that expression (5) essentially generalized scale invariance of the cross sections relative to the transformation of all momenta $P_i \to \lambda P_i$. It is apparent that the quantities b_{ik} are scale-noninvariant, $b_{ik} \to \lambda^2 b_{ik}$, and their ratio is scale-invariant. The conventional principle of scale invariance is formulated as the existence of similarity when the cross sections only depend on the ratio of large values, e.g. the energy variables $(E_1/E_I) = x$. The proposed automodelity principle suggested the existence of scale noninvariance similarity parameters $b_{\alpha k}$ along with x. The study of the similarity laws, which are not due to scale invariance, is one of the goals of the papers[5,7] of the report.

The quantity W^{α} (similarly, W^{β}) is the function of not only the variables b_{ik} but also x_k, i.e. it depends on the direction of the cut connecting the points V_α and V_β. This means that at any, as large as possible, $b_{\alpha\beta}$ the isolated system (cluster) decays anisotropically with respect to the indicated direction in its rest system. Consequently, isotropy in the cluster rest system is not the signature of an isolated cluster ("fireball"). The main signatures of an isolated system (cluster) are the CDP and the automodelity principle.

A lot of regularities observed in experiments of relativistic nuclear physics and high energy hadron physics satisfy the general form of (6).

The relativistic invariant definition of nuclear clusters and hadron jets as a result of manifestation of different states of highly excited nuclear matter in interactions between particles and nuclei is a sufficiently new application of the CDP in the form of (6) for the analysis of multiple particle processes.

One of the most important conclusions of the paper devoted to the analysis of multiple particle production in the relative 4-velocity space is the existence of two characteristic distances in it: $b_1 \sim 0.01$ (nuclear scale) and $b_2 \sim 1$ (quark scale). Two intermediate asymptotic regions, $b_{ik} \gg b_1$ and $b_{ik} \gg b_2$, should correspond to these values. In those regions the probability distributions W as a function of b_{ik} have to satisfy the properties of the general structure of (6), i.e. they must satisfy the automodelity and correlation depletion principles.

In this connection, the clusters with relative velocities of particles inside the cluster, $0.01 \lesssim b_{ik} \ll 1$, characterize highly excited nucleon matter (baryon cluster production) and the clusters with internal relative velocities, $b_{ik} \sim 1$, quark-gluon matter (jet production). The properties of these different 4-dimensional clusters should be described by formulae of the type (6) although they lie in various regions of the kinematical variables.

The results of searching for the studying the properties of the 4-dimensional invariant baryon and hadron clusters are presented below. These data have been obtained by different authors and published in [5].

The data have been obtained with the aid of a 2m propane bubble chamber with Ta plates inside its fiducial volume exposed to beams of 4.2 and 10 GeV/c protons and 4.2 A GeV/c nuclei at the Dubna synchrophasotron and to a beam of 40 GeV/c pions at the Serpukhov accelerator; with the help of a 2m hydrogen bubble chamber ("Ludmila") irradiated with a beam of

22.4 GeV/c antiprotons at the Serpukhov accelerator; with the 76 cm (CERN), 81 cm and 2m (FNAL) hydrogen chambers exposed to 205 GeV/c protons and 5.7 and 12 GeV/c antiprotons, respectively, and a 15-foot bubble chamber, filled with a neon-hydrogen mixture, irradiated with antineutrinos with a mean energy of 35 GeV at FNAL.

In the relativistic invariant approach the baryon clusters and hadron jets are considered as 4-dimensional clusters with relatively small values of b_{ik} in the relative velocity space.

The cluster or jet axis is determined as a single vector $V = \sum_k u_k / \sqrt{(\sum_k u_k)^2}$ that is extracted from the condition of minimum of the quantity

$$\sum_k b_k = -\sum_k (V - u_k)^2 . \tag{8}$$

Summation is performed over all particles belonging to a separate group of particles.

Two clusters (α and β) are separated by minimizing the quantity

$$A_n = \min\left[\frac{1}{n_\alpha} - \Sigma\,(V_\alpha - u_k^\alpha)^2 - \frac{1}{n_\beta}\ \Sigma\,(V_\beta - u_k^\beta)^2\right] \tag{9}$$

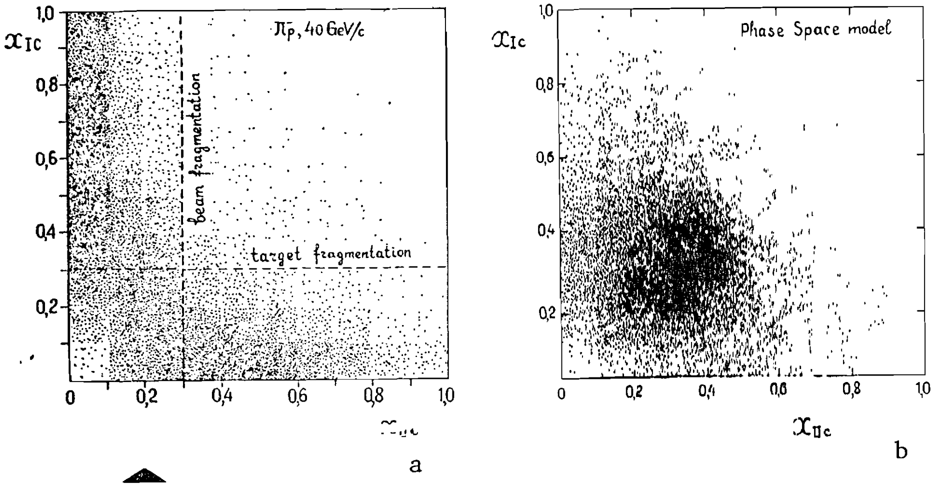
representing the sum of the 4-velocities squared of secondary particles relative to the cluster centres. In this case the following condition is taken as a criterion of cluster separation: the distance between clusters α and β in the 4-velocity space should be $b_{\alpha\beta} \geq 1$ for baryon clusters and $b_{\alpha\beta} \geq 10$ for hadron jets.

To determine the regions of cluster production, the x_{Ic} and x_{IIc} variables are used. The 4-momentum fraction of colliding objects carried away by clusters is characterized by these variables. They can be expressed as

$$x_{Ic} = \frac{m_c^{\alpha(\beta)}}{m_I}\,\frac{(V_{\alpha(\beta)}u_{II})}{(u_I u_{II})} \quad \text{and} \quad x_{IIc} = \frac{m_c^{\alpha(\beta)}}{m_{II}}\,\frac{(V_{\alpha(\beta)}u_I)}{(u_I u_{II})} . \tag{10}$$

Here $m_c^{\alpha(\beta)}$ is the effective mass of cluster α or β, m_I the mass of an incident particle/nucleus and m_{II} the target mass; for the nucleus $m_{II} = m_0$, where $m_0 = 931$ MeV.

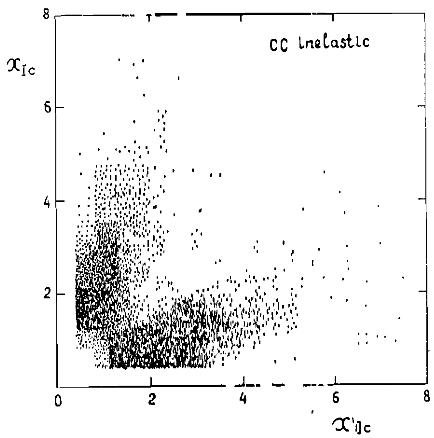
The cluster was assumed to be produced in the projectile fragmentation region for $x_{Ic} > x_{IIc}$ and in the target fragmentation region for $x_{IIc} > x_{Ic}$.



a

b

Fig. 1



c

Figures 1a,b,c illustrate two-dimensional x_{Ic} and x_{IIc} diagrams for events from $\pi^- p$, CC interactions and those calculated by the spherical phase volume model. One can see that real events from $\pi^- p$ and CC interactions in the projectile and target fragmentation regions are separated (clusterized) into two groups of particles. In the case of simulated events such an effect is not observed. The values of the x_{Ic} and x_{IIc} variables used to determine the limits of the fragmentation regions are presented below.

In our analysis the distributions of particles from different interactions have been studied by the following quantities: a) $b_k = -(V - u_k)^2$ is the distance of all selected particles to the cluster centre; b) $b_{Ic} = -(u_I - V)^2$, the distance between the cluster and the projectile; c) $b_{IIc} = -(u_{II} - V)^2$, the distance between the cluster and the target; d) $b_{\alpha\beta} = -(V_\alpha - V_\beta)^2$, the distance between two clusters and so on.

2. STUDY OF THE FIRST INTERMEDIATE ASYMPTOTICS IN THE REGION $0.01 \ll b_{ik} \ll 1$. UNIVERSALITY OF THE PROPERTIES OF 4-DIMENSIONAL BARYON CLUSTERS IN RELATIVISTIC NUCLEAR INTERACTIONS OVER THE ENERGY RANGE $7 \leq b_{I\,II} \leq 570$

According to the classification of relativistic nuclear interactions adopted by us, the given region is separated into two independent subregions: $b_{ik} \sim 10^{-2}$ and $0.1 < b_{ik} < 1$. The first of them ($b_{ik} \sim 10^{-2}$) corresponds to the interaction of nuclei as weakly bound nucleon systems. The proton-neutron model of the nucleus is valid in this region. The second region ($0.1 < b_{ik} < 1$) is intermediate (transitional). Except the nucleon degrees of freedom, the quark degrees of freedom leading to the reconstruction of hadron systems being to manifest themselves in this region.

2.1. Properties of Baryon Clusters in the Region $b_{ik} \sim 10^{-2}$

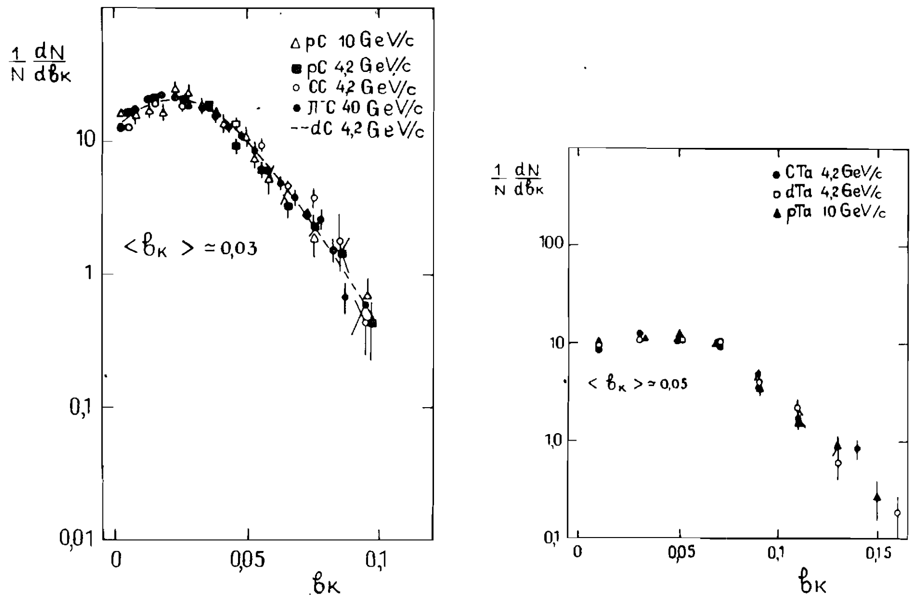
To study the properties of baryon clusters in the region $b_{ik} \sim 10^{-2}$, where we deal with classical nuclear physics, non-interacting (spectator) protons from the target-nucleus and the projectile (for an exposure to carbon), produced in hadron-nucleus (pC, pTa at 4.2 and 10 GeV/c and π^-C at 40 GeV/c) and nucleus-nucleus (CTa and CC at 4.2 A GeV/c) collisions, have been selected. The protons with $150 \leq P_{lab} \leq 300$ MeV or $b_{IIi} = 2(E_i/m_i - 1)$ in the interval $0.025 \leq b_{IIi} \leq 0.1$ were attributed to spectator protons.

Figure 2 a,b shows the b_k distributions of protons for various types of interactions. One can see that the obtained distributions for protons, fragments of the same target-nucleus, are similar within the experimental errors, i.e. they depend on neither the type of interactions nor the energy in the investigated interval $7 \leq b_{III} \leq 570$. An analogous behaviour (see Fig. 3) takes place for the b_{IIc} distributions of protons for various types of interactions.

The following average values of $\langle b_k \rangle$ and $\langle b_{IIc} \rangle$ have been obtained: $\langle b_k \rangle = 0.031 \pm 0.002$, $\langle b_{IIc} \rangle = 0.024 \pm 0.002$ for $(\pi^-, p, d, C) + C$ interactions and $\langle b_k \rangle = 0.048 \pm 0.001$, $\langle b_{IIc} \rangle = 0.031 \pm 0.003$ for $(d, C) + Ta$ interactions in the target nucleus fragmentation region.

Figure 4 presents the b_k, b_{IIc} distributions of stripping protons (i.e. protons with $2.8 \leq P_{lab} \leq 5.4$ GeV/c and $\theta \leq 4^o$ relative to the direction of the projectile motion) produced in CC collisions from the incident carbon nucleus. It is seen that these distributions are similar and the values of $\langle b_k \rangle$ and $\langle b_{Ic} \rangle$ are small: $\langle b_k \rangle = 0.036 \pm 0.001$ and $\langle b_{Ic} \rangle = 0.026 \pm 0.001$.

The foregoing shows that the values of $\langle b_{IIc} \rangle$ and $\langle b_{Ic} \rangle$ are close to the cluster size and much smaller than those of $b_{I\,II}$ for all types of the considered interactions, i.e. $\langle b_{IIc} \rangle \approx \langle b_{Ic} \rangle \approx \langle b_k \rangle \ll b$. Thus, in the region $b_{ik} \sim 10^{-2}$, where the proton-neutron model of the nucleus is valid, the protons from various hadron-nucleus and nucleus-nucleus interactions being fragments of the nucleus represent a system (a 4-dimensional cluster) having a very small size, $b_{ik} \sim 10^{-2}$, in the relative velocity space. This system is characterized by the universal properties depending on neither the type of interactions nor the energy from 4 to 40 GeV/c per nucleon. The asymptotic regime for the production of stripping particles begins even at $E \geq 1$ GeV [6].



a *b*

Fig. 2

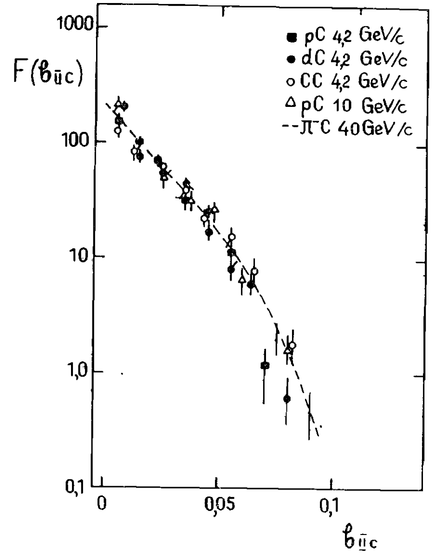
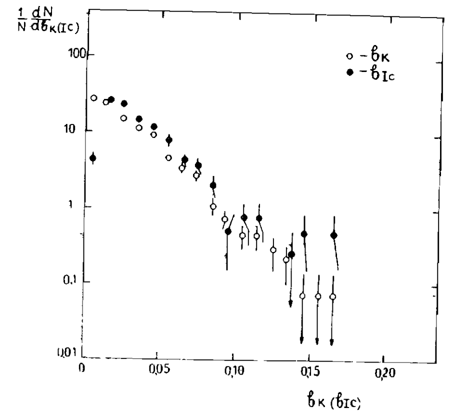


Fig. 3

Fig. 4



2.2. Properties of Baryon Clusters in the Region $0.1 \leq b_{ik} < 1$

The considered b_{ik} region is intermediate. The protons investigated in this region can manifest themselves as quasiparticles in classical nuclear interactions and as fragmentation products of quark systems if the interaction occurs at the quark-gluon level.

The existence of baryon clusters in the $0.1 \leq b_{ik} < 1$ region has been studied for CC interactions at a momentum of 4.2 GeV/c per nucleon. The events with $n_p \geq 4$ were selected. Spectator events from the target-nucleus and the projectile were excluded. It was expected that two proton clusters associated with the target and projectile fragmentation can be produced in most events.

The selection of such two clusters (α and β) and the separation criteria of their production region are described in Section 1. The cluster was assumed to be produced in the projectile fragmentation region when $x_{Ic} > x_{IIc}$ and in the target fragmentation region providing $x_{IIc} > x_{Ic}$. The x_{Ic} and x_{IIc} variables were found from the equations of the energy-momentum conservation laws. With some simplifications they can be expressed in the same manner as (10).

From the above procedure the fraction of selected events was ~86% of all analysed CC interactions. The average multiplicity of protons in clusters was equal to 3.74 ± 0.04 and 3.49 ± 0.04 in the fragmentation regions of the target-nucleus and the projectile, respectively. The average values of $< b_k >$ were found to be 0.324 ± 0.004 and 0.343 ± 0.004.

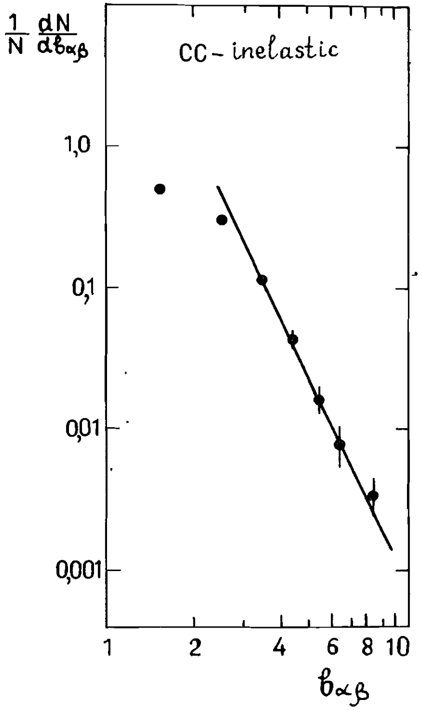


Fig. 5

Figure 5 shows the $b_{\alpha\beta}$ distribution of two clusters. As is seen, in the $b_{\alpha\beta} > 2$ region this distribution is described by a power dependence of the form

$$\frac{dN}{db_{\alpha\beta}} = \frac{A}{b^m_{\alpha\beta}}$$

with $m = 4.3 \pm 0.3$ what agrees with the expected [4] behaviour. In the $b_{\alpha\beta} \geq 1$ region $< b_{\alpha\beta} > = 2.31 \pm 0.03$.

Thus, the clusterization of nucleons also manifested itself distinctly in the transition region, and the average size of 4-dimensional proton clusters is much smaller than the distance between them, i.e. $< b_k > \ll < b_{\alpha\beta} >$.

To study the properties of baryon clusters from CC interactions, we have analysed the invariant distributions of protons from the cluster ($F(b_k)$) and proton clusters of relatively colliding nuclei ($F(b_{II(I)c})$). These distributions are depicted in Fig. 6a,b. The behaviour of the $F(b_k)$ and $F(b_{IIc})$ functions can be presented as two exponents

$$F(b_k) = a_1 \exp(-b_k / < b_k >_1) + a_2 \exp(-b_k / < b_k >_2)$$

with the average values of $< b_k >_1$ and $< b_k >_2$ equal to 0.154 ± 0.014 and 0.288 ± 0.028, respectively, and

$$F(b_{IIc}) = C_1 \exp(-b_{IIc} / < b_{IIc} >_1) + C_2 \exp(-b_{IIc} / < b_{IIc} >_2)$$

with the average values of $< b_{IIc} >_1$ and $< b_{IIc} >_2$ being respectively 0.14 ± 0.02 and 0.51 ± 0.05.

The behaviour of the $F(b_{Ic})$ function for clusters produced in the beam fragmentation region has a similar character.

Consequently, from the behaviour of the $F(b_k)$ and $F(b_{II(I)c})$ functions one can conclude that the production of two types of nucleon clusters is observed in CC interactions: cluster I is characterized by the "temperature" (or the mean kinetic energy of protons in the cluster rest system),

$$< T_k >_1 = \frac{m_N < b_k >_1}{2} = (72 \pm 7) \text{ MeV, and}$$

the 4-velocity value relative to the target nucleus $< b_{IIc} > = 0.14 \pm 0.02$, the second cluster (II) has a higher temperature $< T_k >_2 = (135 \pm 13)$ MeV and $< b_{IIc} >_2 = 0.51 \pm 0.02$. It has been found that the part of all CC inelastic events, forming cluster I, is ~ 87% and cluster II, ~ 13%.

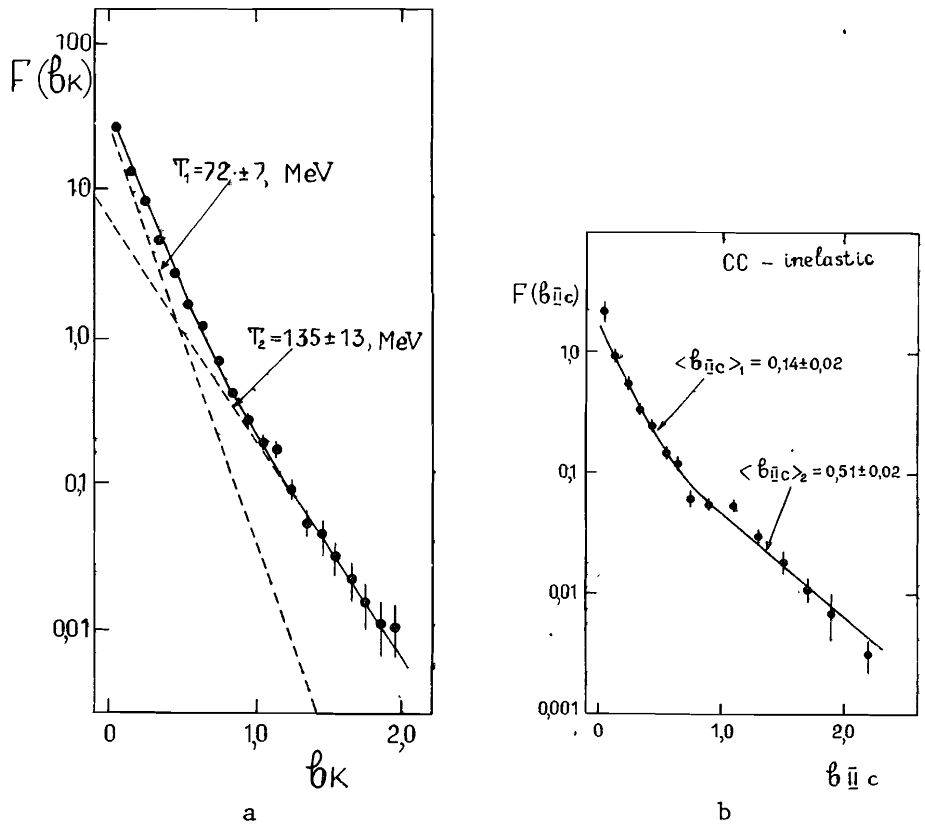
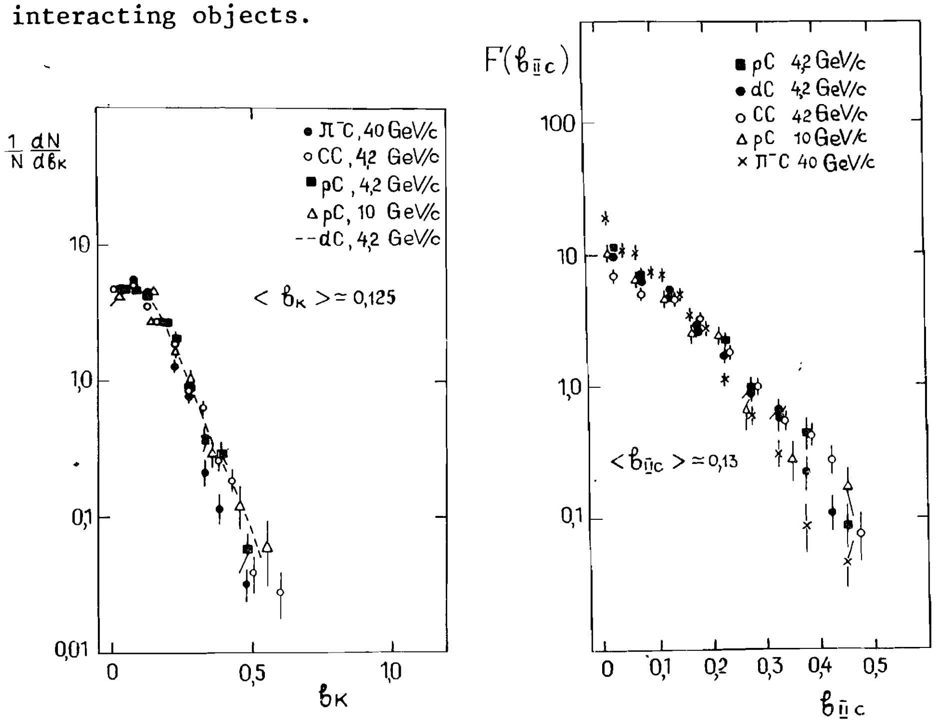


Fig. 6

Figure 7a,b presents the behaviour of the characteristics of nucleon clusters as a function of the type and energy of interacting objects.



a *b*

Fig. 7

To provide similar conditions for comparison of various nuclear reactions, the protons with $300 \le P_{lab} \le 800$ MeV/c were selected. There must be no less than two of such protons in the event. The clusters selected in this way belong essentially to the type "cluster I". From the figures one can see that for a wide class of nuclear reactions over an energy interval of $7 \le b_{III} \le 570$:

(a) the cluster size ($\langle b_k \rangle$) is similar;

(b) the proton cluster 4-velocity relative to the parent target-nucleus is of the order of the cluster size, i.e. $\langle b_{IIc} \rangle \approx \langle b_k \rangle$;

(c) the distribution of nucleon clusters relative to the target-nucleus in universal;

(d) for π^-C interactions at 40 GeV/c there is a ~ 20% deviation of the indicated values what can be explained by the influence of the quark-gluon degrees of freedom at these energies.

Thus, the property of baryon clusterization distinctly manifests itself in the transitional $0.1 < b_{ik} < 1$ region of relativistic nuclear collisions. For the first time two types of 4-dimensional baryon clusters are directly separated. They differ from one another by their properties: one of them is characterized by $\langle T_k \rangle_1 = (72 \pm 7)$ MeV and $\langle b_{IIc} \rangle = 0.14 \pm 0.01$, another by $\langle T_k \rangle_2 = (135 \pm 13)$ MeV and $\langle b_{IIc} \rangle_2 = 0.51 \pm 0.05$. The mean size of proton clusters, $\langle b_k \rangle$, is $3 \cdot 10^{-1}$ and $\langle b_{IIc} \rangle = 10^{-1}$.

In the 4-velocity space the properties of baryon clusters (cluster I in our case) have a universal character depending on neither the type of interactions nor the collision energy in an interval of $7 < b_{I\,II} < 570$. This fact should be considered as a manifestation of the automodelity properties in the region of small b_{ik} and as a generalization of the phenomenon known as "nuclear scaling". Nuclear scaling is the invariance of cross sections with changing the collision energy; automodelity also implies the independence of the $b_{II\alpha}$, $b_{I\beta}$, $b_{\alpha\beta}$ variables and other large b_{ik}.

3. STUDY OF THE SECOND INTERMEDIATE ASYMPTOTICS IN THE $b_{ik} \gg 1$ REGION. UNIVERSALITY OF THE PROPERTIES OF 4-DIMENSIONAL HADRON JETS AND OBSERVABILITY OF COLOUR CHARGES

In the $b_{ik} \gg 1$ region, hadrons lose the meaning of quasiparticles of nuclear matter, and the interaction occurs at the quark-gluon level. This region is most favourable for studying the hadron jet properties as, according to the present-day notations, the hadron jets are the products of conversion of the quark or gluon, knocked out in the collision of primaty particles, to hadrons.

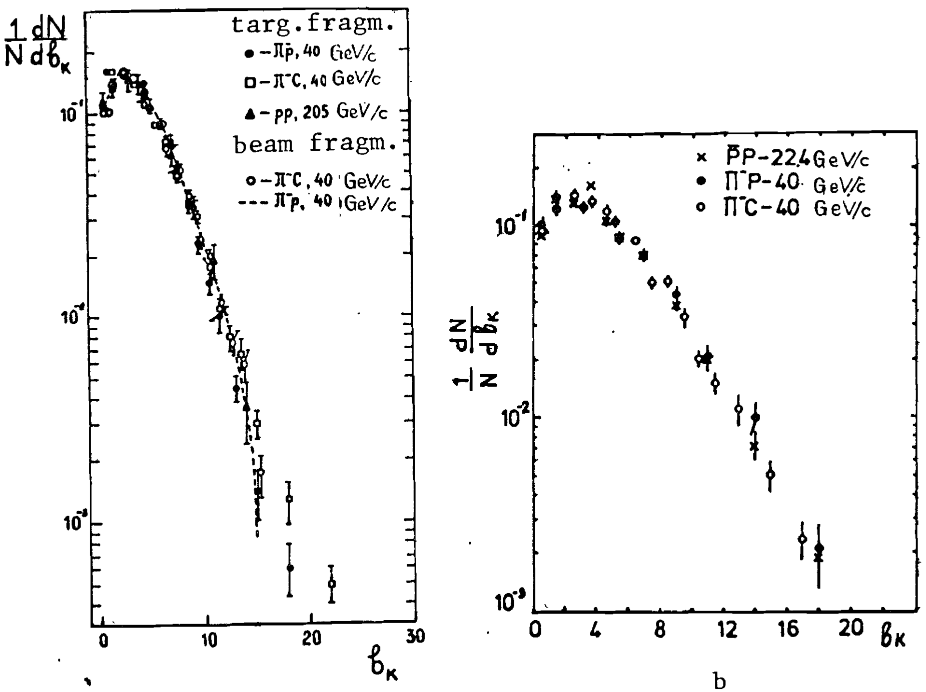
In the relativistic invariant approach the jets are considered as hadron 4-dimensional clusters with relatively small values in the relative velocity space.

As the studies in the field of relativistic nuclear physics show /2/, the transition of hadron interactions to the quark-gluon level is accomplished already for $b_{ik} \gtrsim 5$. From here it follows that the jets have to be separated even for $(V_{II} u_I) \sim (V_I u_{II}) \approx 3.5$ (V_{II} and V_I are the jet axes in the fragmentation regions of particles II and I), and the jet width in the considered space should be approximately equal to the same value.

The determination of the jet axis and the selection method of particles belonging to the jet are similar to those already used in the study of baryon clusters (see Section I). Two jets will be separated in the relative 4-velocity space if the condition $b_{\alpha\beta} > 10$ is fulfilled. To separate the jets produced in the fragmentation regions of colliding objects, the x_{Ic} and x_{IIc} variables were used which characterize the 4-momentum fraction of primary particles carried away by the jet (see (10)). For the jets produced in the fragmentation regions of the projectile and the target, the following values of the variables were respectively chosen: $x_{Ic} \gtrsim 0.3$ and $x_{IIc} < 0.3$; $x_{IIc} \gtrsim 0.3$ and $x_{Ic} < 0.3$. The experiment showed that the number of unseparated events (i.e., belonging to the region $x_{Ic} > 0.3$ and $x_{IIc} > 0.3$) was $\sim 2\%$.

The analysis was performed using a set of experimental data on hadron-hadron ($\pi^- p$, pp, $\bar{p}p$), hadron-nucleus ($\pi^- C$, pC) and $\bar{\nu}N$ interactions of various types over an energy range from 6 to 205 GeV.

Figure 8a,b presents the b_k distributions of π^--mesons normalized to unity for $\pi^- p$, $\pi^- C$, pp and $\bar{p}p$ interactions in the beam and target fragmentation regions. According to the auto-



a

b

Fig. 8

modelity and correlation depletion principles, in the $P_{lab} \geq 22$ GeV/c region the properties of 4-dimensional jets (clusters) depend on neither the process, in which they are produced, nor the collision energy. As expected, the average values of $\langle b_k \rangle$ are equal to $\sim 3 \div 4$.

The coincidence of the distributions for $\pi^- p$ and $\pi^- C$ cumulative interactions as a function of the scale noninvariant parameter b_k in the beam and target fragmentation regions means that the fragmentation functions of quarks, diquarks and multiquark systems into pions have a universal character in the relative 4-velocity space. From these data it also follows that the carbon nucleus has no influence on hadron jet production, i.e. they are mostly produced outside the nucleus.

The observed universality of the hadron b_k distributions, i.e. independence of the type of a fragmenting object (π^-, p, $\bar{p}$, C) and the collision energy at $P_{lab} \geq 22$ GeV/c, means that the hadronization of quarks, diquarks and multiquark systems in these variables is the same at high energies, and it can be interpreted as a characteristic of colour charge interaction with vacuum irrespective of other properties of the system carrying a colour charge (quark or diquark). In this connection, it is of great importance to study the properties of hadron jets applicable to hard processes, in which the jets are produced in the hadronization of colour objects in vacuum. With this aim we have made the analysis of the hadron jet properties in deep inelastic lepton-nucleon collisions in which, according to the existing notations, the "isolated" quark, hadronized in vacuum, and the diquark, which hadronization is similar to the soft one of quarks and diquarks in hadron-hadron collisions, are produced.

In the analysis we have used the experimental material on $\bar{\nu}N$ interactions obtained at $\langle E_{\bar{\nu}} \rangle = 35$ GeV by the IHEP-ITEP-FNAL and Michigan University Collaboration.

The events with $Q^2 = -q^2 \geq 1$ (GeV/c)^2 and $x = \frac{Q^2}{2M\nu} \geq 0.1$ have been selected to separate deep inelastic $\bar{\nu}N$ collisions with valent u-quarks, where q is the 4-momentum transferred to the nucleon, M the nucleon mass and $\nu = E_{\bar{\nu}} - E_{\mu^+}$ the energy of hadrons in the laboratory system. For separation of the multiple particle production region $W^2 \geq 9$ GeV^2 (W is the total hadron energy in the c.m.s.). The conditions $\sum_i e_i = 0$ or 1 and $n_N \leq 1$ (e_i is the charge of secondary particles and n_N the number of secondary nucleons in the interaction) are used to exclude nuclear effects that are due to cascade nucleon reproduction in the neon nucleus.

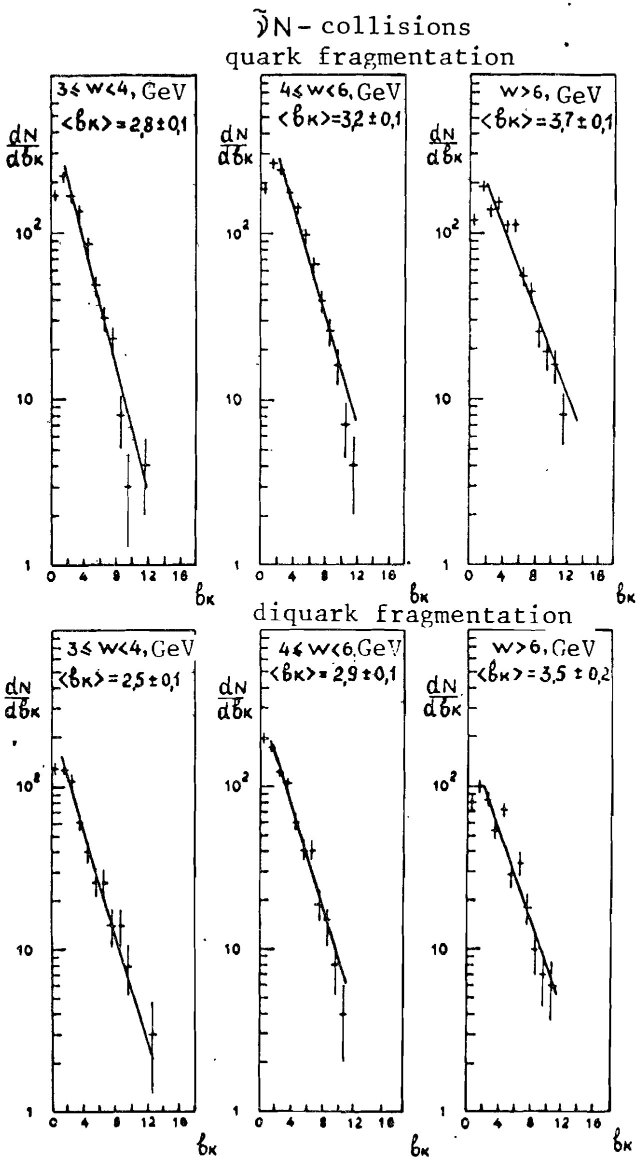


Fig. 9

Figure 9 shows the distributions of $\pi^{\pm}$-mesons in the jets produced in the fragmentation of knocked-out quark and diquark for three energy intervals of the hadron system. The particles, belonging to one or another jet, are selected with the aid of the invariant variables

$$x_q = \frac{(P_{qq}\cdot P_k)}{(P_q\cdot P_{qq})} \gtrsim 0.1 \qquad \text{and} \qquad x_{qq} = \frac{(P_q\cdot P_k)}{(P_q\cdot P_{qq})} \gtrsim 0.1, \tag{11}$$

where $P_q = xP_N + q$, $P_{qq} = (1-x)P_N$. Here P_N and P_k are the 4-momenta of a nucleon and a k-th particle. In the $b_k \geq 2$ region all the distributions have an exponential character $\exp(-b_k/<b_k>)$ and are similar within the experimental errors for the quark and diquark fragmentation at the same energy W. As in the case of soft processes, the average jet size, $<b_k>$, is equal to ~ 4.0 at the same energy in the c.m.s.

Thus, in the relative 4-velocity space the properties of 4-dimensional hadron jets in soft and hard interactions are universal and independent of neither the type of a fragmenting system (π^-, p, $\bar{p}$, C, q, mq) nor the primary collision energy at $\sqrt{s} = W \gtrsim 6$ GeV. This shows evidence that the jet properties are determined by the neutralization of colour charge in vacuum, the process is statistical in character and independent of the production method.

As is seen from Fig. 10, the independence of the jet properties (their universality) reaches the asymptotic regime at $W \geq 6$ GeV (or at $E_q(E_{qq}) \gtrsim 3$ GeV). According to the CDP, from these data it follows that at energies higher than those in our studies the hadron jet properties should be the same as in Fig. 8a,b because, as could be expected, the "separation" into clusters/jets becomes stronger with increasing b_{III}.

As noted above, according to the CDP, in the relative 4-velocity space the probability W as a function of the b_{ik} variables should have the $b_{\alpha\beta}$ properties of automodelity assuming asymptotically large values.

$$W(b_{\alpha\beta}, b_{\alpha i}, b_{\beta i}, \ldots) \rightarrow \frac{1}{b^m_{\alpha\beta}} W(b_{\alpha i}, \frac{b_{\beta i}}{b_{\alpha\beta}}, \ldots). \tag{12}$$

The properties of W as a function of the $b_{\alpha k}$ and $b_{\beta k}$ variables for different types of interactions have been discussed above. Now we want to present results of the study of the behaviour of the W distribution versus in light front variable

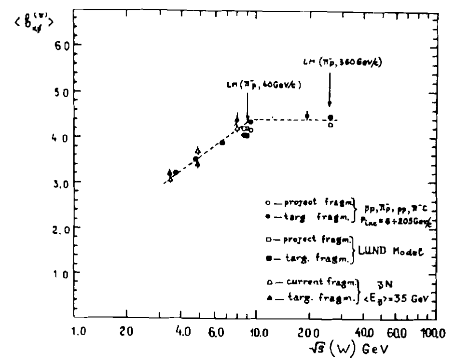


Fig. 10

for particle k: $x_k = \frac{b_{\alpha k}}{b_{\alpha\beta}}\Big|_{b_{\alpha\beta}\to\infty} \to u^{\alpha}_{k0} - u^{\alpha}_{kz}$. A accordance with the above general principles, one can expect that the properties of the W distributions as a function of the scale invariant parameter of similarity (x_k) should satisfy the automodelity principle in the $b_{ik} \gtrsim 5$ region, and the isolated systems (4-dimensional jets α and β in our case) should decay anisotropically in the rest frame of the system/jet with respect to the direction of the cut joining points V_α and V_β in the relative velocity space.

These and other hadron jet properties have been studied by analysing the characteristics of 40 GeV/c $\pi^- p$, $\pi^- C$ and 205 GeV/c pp interactions.

The x_k distribution of π^--mesons in the jets is shown in Fig. 11. This distribution as well as the b_k distributions studied previously are similar for the jets produced in the beam target fragmentations, and their behaviour depends on neither the type nor the energy of collisions in an interval from 40 to 205 GeV. This means that the hadron jet properties are universal for the fragmentations of various quark systems (q, qq, mq) in the considered energy range.

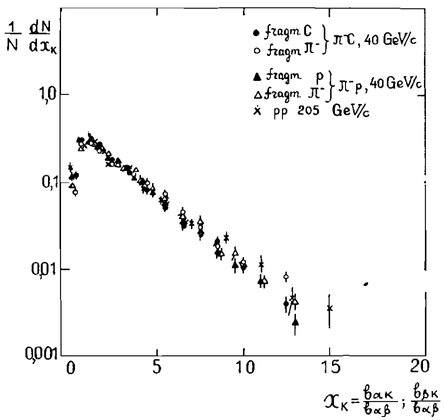


Fig. 11

Figure 12a,b illustrates the $|\cos\theta|$ distribution of π^--mesons in the jet rest system, where θ is the angle between the velocity vector of particle $\vec{u}_s$ in this system and vector $\vec{V}_{\alpha\beta}$. In fact, the distributions for all types of interactions have an anisotropic character.

To determine the values of parameter m in Eq.(12), the $b_{\alpha\beta}$ distributions of hadron jets α and β have been studied. These distributions are presented in Fig. 13. As expected, the distributions from $b_{\alpha\beta} > 2$ have a power dependence of the form $\sim \frac{1}{b^m_{\alpha\beta}}$ with $m = 3.1 \pm 0.1$ independent of the type and the collision energy in an interval from 40 to 205 GeV within the experimental errors.

We have also studied the invariant distributions of hadron jets versus their 4-velocities relative to the target (b_{IIc}) and the incident particle (b_{Ic}).

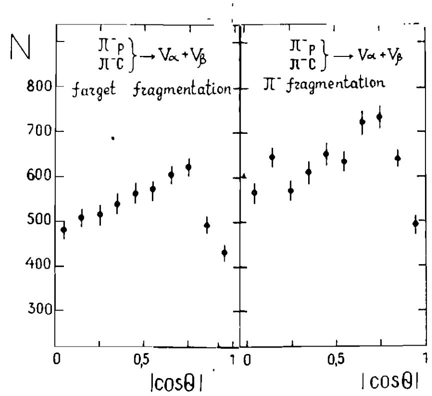
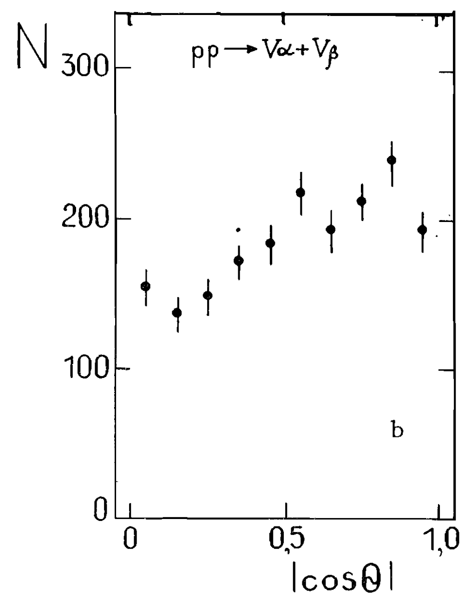


Fig. 12

a



b

Figure 14a,b,c shows that the behaviour of these distributions has an exponential dependence of the type

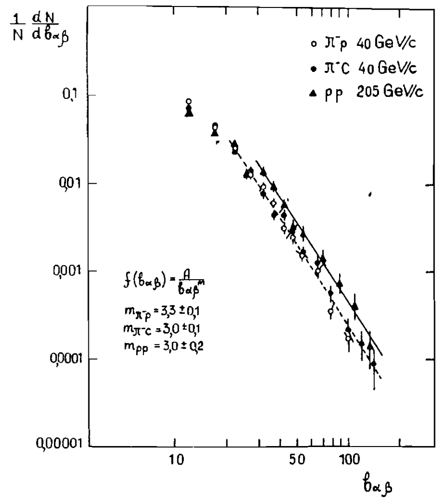


Fig. 13

$\sim \exp(-b_{I(II)c} / \langle b_{I(II)c} \rangle)$

with the following average values of $\langle b_{I(II)c} \rangle$: $\langle b_{IIc} \rangle = 1.61 \pm 0.06$ in the target fragmentation region and $\langle b_{Ic} \rangle = 10.1 \pm 0.4$ in the projectile fragmentation region, i.e. the avegage relative velocity of the jet from protons is much smaller than the one for the jet from pions. Under similar selection conditions the ratio $\langle b_{Ic} \rangle / \langle b_{IIc} \rangle$ is $6.2^{+0.5}_{-0.3}$ what approximately equals the proton to pion mass ratio. Substituting the proton and pion masses in the expressions for relative 4-velocities b_{Ic} and b_{IIc} for some effective mass M and performing the corresponding transformations, we obtain the result [7] that can be formulated as follows: the quark objects with equal

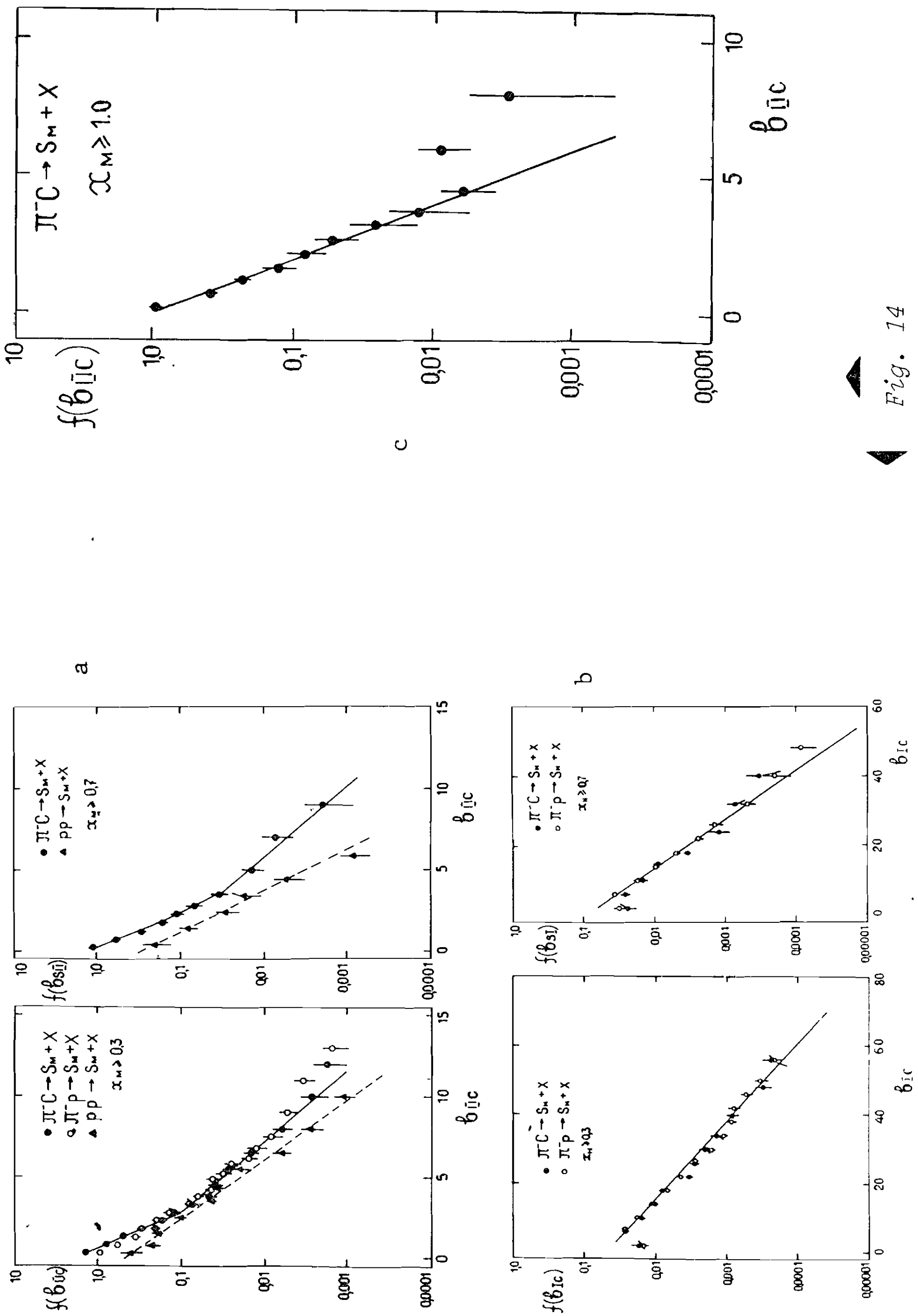


Fig. 14

effective mass independent of the type of a fragmenting system (π, p, C) are the sources of hadron jets.

Thus, in the asymptotic region of large b_{ik}($b_{ik} \geq 5$) the clusterization of hadrons (hadron jet production) is observed in the beam and target fragmentations. The 4-dimensional hadron jets have universal properties depending on neither the type of a fragmenting system (π^-, p, $\bar{p}$, C, q) nor the collision energy. The asymptotic regime takes place at $\sqrt{s} \geq 6$ GeV.

The observed universality of the jet properties, i.e. their independence of the production process, can be interpreted as a result of colour interaction with QCD vacuum.

In connection with the said above, interest has been aroused in the question on the possibility to observe objects with colour charges. There exists an opinion that objects (e.g., quarks and gluons) are unobservable because they strongly interact with vacuum fluctuations and immediately convert to hadrons.

However, let us consider the conditions of observability of known unstable particles. The most important criteria of their observability are the following: a) the cross sections (σ) can be presented as $\sigma = \sigma_p W_d$ with a sufficient precision, where W_d is the decay probability of a particle or a secondary interaction and σ_p the production cross section; b) universality, independence and relativistic invarriance of W_d. As known, the properties of W_d are reliably detected in experiment. The properties of unstable particles are determined by those of W_d, i.e. their observability takes place.

By analogy, if we know the properties of invariant universal jets, we can also determine the properties of quarks and gluons. From this it follows that the observability conditions of quarks completely satisfy the criteria a) and b). It should be noted that the universality of the jet properties ensures that quarks and gluons survive over a long period of time to cover the distance larger than the size of the parent system (see, e.g., Fig. 8a,b).

Consequently, the observed universality of W^{α}, W^{β} and so on, i.e. the similarity of their properties in different reactions, and their invariance show evidence for the observability of objects having colour charges.

4. COLCLUSIONS

Our analysis of different hadron and nuclear multiple particle production processes in a wide energy range made in the frame of the new relativistic invariant approach to these processes has established the following:

1. The classification criteria of relativistic nuclear interactions suggested in papers [2,3] are valid: the $0.01 < b_{ik} < 0.1$ region corresponds to classical nuclear physics and the proton-neutron model of the nucleus holds true in it; $b_{ik} \gg 1$ corresponds to the region in which hadrons lose the meaning of quasi-particles of nuclear matter, and the interaction occurs at the quark-gluon level; the $0.1 < b_{ik} < 1$ region is intermediate where the quark degrees of freedom play a significant role in hadron system reproduction (perestroika).

2. The general principles, namely the automodelity and correlation depletion ones, allowing one to give a universal description to the asymptotic hadron properties have been formulated. According to these principles, the validity of the conclusion of the existence of two b_{ik} regions is shown. These regions are characterized by different asymptotic properties of highly excited nuclear matter: in the first of them ($0.01 \ll b_{ik} \ll 1$) there take place the asymptotic properties of highly excited nuclear matter, in the second one ($b_{ik} \sim 1$) the asymptotic properties of highly excited hadron matter.

3. The properties of baryon clusterization manifest themselves distinctly in the first intermediate asymptotics in the $b_{ik} \ll 1$ region. Two types of 4-dimensional baryon clusters that differ from one another by their properties have been first separated. The first cluster has $\langle T_1 \rangle = (72 \pm 7)$ MeV, where $\langle T_1 \rangle$ is the average kinetic energy of protons in the rest system, and it is nearer the parent nucleus ($\langle b_{IIc} \rangle_1 = 0.14 \pm 0.02$) in the relative 4-velocity space; the second one has $\langle T_2 \rangle = (135 \pm 13)$ MeV and is more distant from the parent nucleus.

The average size of 4-dimensional baryon clusters, is $3 \cdot 10^{-1}$, and $\langle b_{IIc} \rangle$, as expected, equals $\sim 10^{-1}$. The properties of 4-dimensional baryon clusters-I have a universal character dependent on neither the type of interactions nor the collision energy in an interval of $7 \lesssim b_{III} \lesssim 570$. This fact should be considered as the generalization of the phenomenon known as "nuclear scaling".

4. In the second intermediate asymptotics in the $b_{ik} \gg 1$ region hadron jet (4-dimensional hadron cluster) production is mainly observed in the beam and target fragmentation regions. It has been found that the 4-dimensional hadron jets from soft and hard processes have universal properties, i.e. they depend on neither the type of a fragmenting system (π^-, p, $\bar{p}$, C, q) nor the primary energy. The asymptotic regime occurs at $b_{J_1 J_2} \gtrsim 10$. The universality of the hadron jet properties, i.e. their independence of the process in which they are produced, makes it possible to interpret them as a characteristic of colour charge interaction with QCD vacuum. The observed properties (universality, independence of the reaction type and relativistic invariance) of 4-dimensional hadron jets prove the possibility of determination of quark and gluon properties, i.e. the possibility of observability of objects having colour charge.

The authors would like to express their gratitude to A.M.Baldin for numerous discussions and support in this work.

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Received by Publishing Department
on November 24, 1987.

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Гришин В.Г., Диденко Л.А., Кузнецов А.А. E1-87-829

Поиск и исследование асимптотических свойств высоковозбужденной ядерной материи

С помощью нового релятивистски-инвариантного метода анализируются процессы множественного рождения в пространстве, точками которого являются четырехмерные скорости $u_i = P_i/m_i$, а основными переменными - $b_{ik} = -(u_i - u_k)^2 = 2[(u_i u_k) - 1]$, где P_i - четырехимпульсы частиц и m_i - их массы. В релятивистски-инвариантном подходе сформулированы асимптотические свойства сечений адронных и ядерных процессов при $b_{ik} \to \infty$. Наиболее важные из этих закономерностей - принцип автомодельности и принцип ослабления корреляций, установлены экспериментально. В соответствии с этими принципами экспериментально показано существование двух асимптотических областей по переменной b_{ik}, характеризующихся различными свойствами высоковозбужденной ядерной материи - нуклонной и адронной. Обнаружено, что в первой их этих областей /$0,01 \ll b_{ik} \ll 1$/ имеет место преимущественное образование барионных кластеров, а во второй /$b_{ik} \gg 1$/ - адронных струй.

Работа выполнена в Лаборатории высоких энергии ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1987

Didenko L.A., Grishin V.G., Kuznetsov A.A. E1-87-829

Search for and Study of the Asymptotic Properties of Highly Excited Nuclear Matter

In the invariant method of analysing multiple particle production, these processes are considered in a space the points of which are the 4-velocities $u_i = P_i/m_i$ where P_i are the 4-momenta and m_i the masses of particles, and $b_{ik} = -(u_i - u_k)^2 = 2[(u_i \cdot u_k) - 1]$ are basic variables. General asymptotic properties of the cross sections of hadron and nuclear processes at $b_{ik} \to \infty$ have been formulated as relativistically invariant in these variables. The most important of these regularities, the automodelity principle (substantially generalizing scale invariance) and the correlation depletion principle, have been experimentally substantiated. According to the automodelity and correlation depletion principles, the existence of two asymptotic b_{ik} regions has been established experimentally. These regions are characterized by different properties of highly excited nuclear matter (nucleon and hadron). It has been found that baryon clusters are mostly produced in the first region ($0.01 \ll b_{ik} \ll 1$) and hadron jets in the second one ($b_{ik} \gg 1$).

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1987