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HADRON JETS AND NUCLEON CLUSTERS IN THE RELATIVISTIC NUCLEAR COLLISIONS

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1. INTRODUCTION

At present the physics of relativistic heavy ion collisions takes a leading place in the programm of investigations at the largest accelerators of the world[1].

Such increasing interest of nuclear and particle physicists in these investigations is not casual. It is mainly motivated by hopes to obtain the states of highly excited nuclear matter including both the possibility of colour deconfinement and the réalization of phase transition from hadronic matter to quark-gluon plasma (QGP).

Theoretical calculations made in the frame of the lattice QCD[2] predict that the mentioned states can be obtained in relativistic nuclear collisions either by "heating" the nuclear matter to the temperatures 150-200 MeV and low quark density or by "compression" at substantially low temperatures if the density is approximately 5 times as large as the normal nuclear density which is around 0.15 GeV/fm^3.

These predictions are of great importance not only for the physics of elementary particles and atomic nucleus, but also for the astrophysics and cosmology[3].

The search for and study of both the transition and properties of the primordial QGP are directly connected with the problem of colour charge deconfinement and its behaviour at large distance where, as is known, the modern theory still works badly. The production of QGP helps to realise the hypothetic states of matter in the laboratory which in the early Universe took place in the iniverse direction some 10^{-5} seconds after the Big Band and the possibility of studying these states at different stages of time up to the cooling of QGP (cosmic expantion) and its transformation into colourless objects-Hadrons (hadronization process).

On the other hand, observation and study of the properties of a plasma of deconfined quarks and gluons will allow one to understand the nature of neutron stars and other cosmic objects which can be in the phase of plasma.

In order to interpret these theoretical notions to the Language of facts obtained in studies, it is necessary to set up some heavy ion experiments at high energies which will provide one with unambiguous answer to such questions as: what kind of state is the state of highly excited nuclear matter in terms of the observed values? Does any similarity of excited matter thermalization appear? How could one observe the exhibition of quark-gluon degrees of freedom and colour deconfinement? The results of many groups of physicist working in the field of relativistic nuclear physics are in part devoted to the answers to these questions.

The observation and study of the cumulative effect[4] and EMC results on deep-inelastic scattering of muon on nuclei[5] have shown that the quark-parton structure functions of nuclei qualitatively differ from the quark-parton structure functions of nucleons in nuclei and cannot de reduced to the superposition of the latter. The data on pion production in the cumulative region ($x > 1$) for the first time gave an indisputable evidence for the existence of multiquark (6q, 9g etc) configurations in nuclei[6].

A number of interesting and unusual phenomena which are considered as an indication of a possible existence of QGP have been observed in CERN andBNL experiments after realizing the acceleration of ^{16}O and ^{32}S ions up to 200 A GeV and ^{16}O and ^{28}Si to 14.5 A GeV, respectively. In particular, the effect of J/Ψ suppression[7] and an intensified yield of strange particles in nucleus-nucleus collisions with respect to hadron-nucleus and nucleon-nucleon ones were found[8]. Although we have more standard explanations to data (besides the interpretations of these and other observed effects as signals of the QGP existence), the CERN and BNL experiments give much important information on the collisions of relativistic heavy ions. This information allows one not only to feel but also to understand these processes at energies achievable under laboratory conditions.

A direct method to observe colour degrees of freedom is to investigate the production of hard/semihard QCD jets. In the case of relativistic nuclear collisions the study of cumulative jets is of great importance[9], because reactions of this type are at most "cleaned" from the processes connected with nuclear effects. As theoretical calculations show, the production of jets in relativistic nucleus-nucleus collisions serves as a probe for excited nuclear matter. In particular, studying the factor of jet quenching over various periods of heavy ion collisions and at different energies, one can not only obtain information on the state of excited hadron matter but also identify the realization of phase transition of hadron matter to quark-gluon plasma.

The present investigation is mainly devoted to search for and study of the states of highly excited nuclear matter in different types of nucleus-nucleus and hadron-nucleus collisions over an energy interval of 4.0-205 GeV/c by studying the properties of baryon clusters and hadron jets with the aid of a new relativistic invariant method in the space of relative 4-velocities.

2. DATA ANALYSIS

In contrast to the traditional methods (e.g., inclusive, semi-inclusive and so on), the relativistic invariant allows us not only to apply experimental information in full but also to order a complicated picture of nuclear collisions at high energies[10].

In the new method the processes of multiple particle production $I + II \to 1 + 2 + \ldots$ are considered in a space the points of which $U_i = P_i/m_i$ are 4-velocities and positive invariant dimensionless quantities $b_{ik} = -(u_i - u_k)^2$, where $i, k = I, II, 1, 2, \ldots$, are basic variables describing the relative particle motion in this space.

Introduction of the conception of relative distances into the 4-velocity space allows one to define and to observe four-dimensional clusters in this space which are either hadron jets or baryon clusters. It has been found also that baryon clusters are mostly produced in the region $0.01 \ll b_{ik} < 1.0$; and hadron jets, in the second one $b_{ik} \gg 1$.

By clusters are meant groups of points u_i (each point corresponds to the real particle) and distance between them b_{ik} is much smaller than the average distance between all the points of the set or than the average distance between particles along the whole phase volume of the reaction.

The center of cluster (or jet axis) is determined as a single 4-vector $V_\alpha = \sum_k u_k / \sqrt{(\sum_k u_k)^2}$ extracted from the condition of minimum of the quantity $\sum_k b_k = -\sum_k (V_\alpha - u_k)^2$. Summation is performed over all particles belonging to a separate group of particle "α". For example, two clusters ("α" and "β") are separated by minimizing the quantity

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

representing the sum of the 4-velocities squared of secondary particles relative to the cluster centers V_α and V_β (see Fig.1).

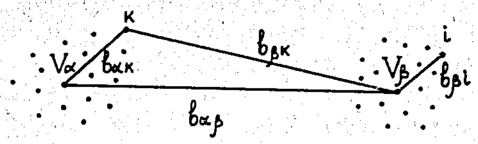


Fig.1

In this case the following condition is taken as a criterion of cluster separation: the distance between clusters α, β in the 4-velocity space should be $b_{\alpha\beta} \gtrsim 1{,}0$ for baryon clusters and $b_{\alpha\beta} \gtrsim 10.0$ for hadron jets.

To determine the region of cluster production, the X_{IC} and X_{IIC} variables are used:

$$X_{IC} = \frac{m_C^{\alpha(\beta)}}{m_I} \cdot \frac{(V_{\alpha(\beta)} \cdot u_{II})}{(u_I \cdot u_{II})}.$$

$$X_{IIC} = \frac{m_C^{\alpha(\beta)}}{m_{II}} \cdot \frac{(V_{\alpha(\beta)} \cdot u_I)}{(u_I \cdot u_{II})},$$

where $m_C^{\alpha(\beta)}$ is the mass of cluster "α" (or β), m_I (m_{II}) is the mass of projectile (or target). We consider that the cluster is formed in the projectile fragmentation region if $X_{IC} > X_{IIC}$ and $X_{IIC} > X_{IC}$ in the target fragmentation region.

In the further analysis the following quantities are used to characterize different properties of clusters and their particles:

$b_k = -(V - u_k)^2$

- is the distance between all selected particles and the centre of the cluster;

$$F(b_k) = \frac{2}{m^2} \int \frac{1}{\sqrt{b_k^2 + b_k^2/4}} \cdot \frac{d\sigma}{db_k d\Omega} d\Omega$$

- is invariant cross section $E\frac{d\sigma}{d\vec{p}}$ expressed in b_k and integrated on angular variables;

$b_{I(II)C} = -(u_{I(II)} - V)^2$

- is the distance between the cluster and projectile (or target);

$F(b_{II(I)C})$

- represents invariant cross section $E_C\frac{d\sigma}{d\vec{p}_C}$ expressed in b_{II} or b_I and integrated on angular variables. The function $F(b_{II(I)C})$ is written in the analogous manner $F(b_k)$.

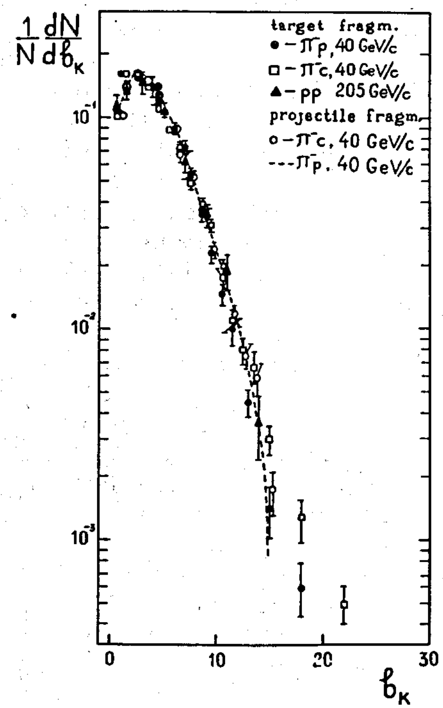
The results of searching for and the studying of the properties of 4-dimensional invariant baryon clusters and hadron jets are presented below.

3. PROPERTIES OF HADRON JETS

The use of b_{ik} for the analysis of hadron jet properties production, which is connected with the quark structure of hadrons and nuclei, allows one to simplify the analysis of experimental information and to obtain a set of new interesting regularities[11].

The data on cumulative particle production in different types of relativistic nuclear reactions I + II → 1 + 2 +... have shown that quark degrees of freedom are of great importance when $b_{ik} \gtrsim 5$. This means that jets were expected to be separated already for $(U_I V) \simeq (U_{II} V) \simeq 3.5$ and the width of the 4-dimensional jets to be equal to about the same value.

Figures 2a,b present the b_k distributions of pions from jets (separated using the approach discribed in section (2) norma-



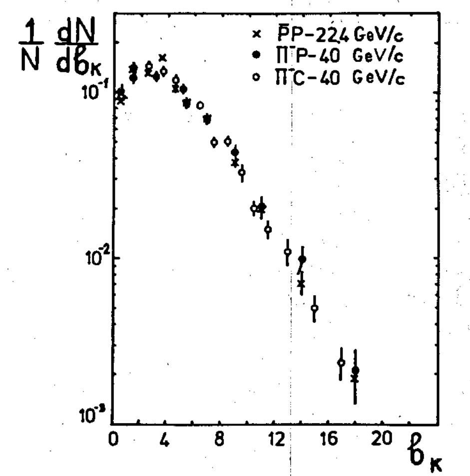


Fig.2

lized to unity for $\pi^- p$, $\pi^- C$ (40 GeV/c), $\bar{p}p$ (22.4 GeV/c), pp (205 GeV/c) in the beam and target fragmentation regions. One can see that the properties of the 4-dimensional hadron jets depend on neither the process, in which they are produced, nor the collision energy within an interval of 22.4-205 GeV. As was expected, the average values of $< b_k >$ (or the width of the 4-dimensional jet) are equal to 3.0-4.0.

The coincidence of the properties of the b_k distributions from pion jets for $\pi^- p$ and $\pi^- C$ interactions in the regions of target and projectile fragmentation, means that hadronization of quarks and diquarks into hadrons in these variables has a universal character and does not depend on the properties of the parent system. These data show also that the carbon nucleus does not affect the process of parton hadronization and it takes place, apparently, outside the nucleus.

The observed universality of the b_k distributions 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 QCD 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 jet applicable to hard processes, in which the jets are produced as a result of hadronization of colour objects in vacuum. For this purpose we have analysed the jet properties produced in $\tilde{\nu}$ N collisions. The experimental information is obtained by the USSR-USA collaboration with the aid of 15-foot bubble chamber, filled with a neon-hydrogen mixture, irradiated with antineutrinos at energy $< E_{\tilde{\nu}} > \simeq 35$ GeV.

According to the existing conceptions, the "isolated" (knocked-out) quark, hadronized in vacuum, and the diquark, which hadronization is similar to the soft one of quarks (diquarks) in hadron-hadron collisions, are produced in the case of $\tilde{\nu}$N interaction.

Figure 3 presents teh b_k distributions in jets produced by the fragmentation of the knocked-out quark and the left diquark. One can see that in the domain b_k distributions are similar with experimental errors and the sizes of the jets are equal to $b_k \sim 4.0$ at the same energy in the c.m.s.

Thus, in the relative 4-velocity space the properties of hadron jets in soft and hard interactions are universal, i.e. independent of neither the type of a fragmentating system (π^-, p, $\bar{p}$, C, q, qq or mq) nor the primary collision energy.

As is seen from Fig.4, the universal of the jet properties reaches the asymptotic regime at $S \gtrsim \sqrt{6}$ GeV.

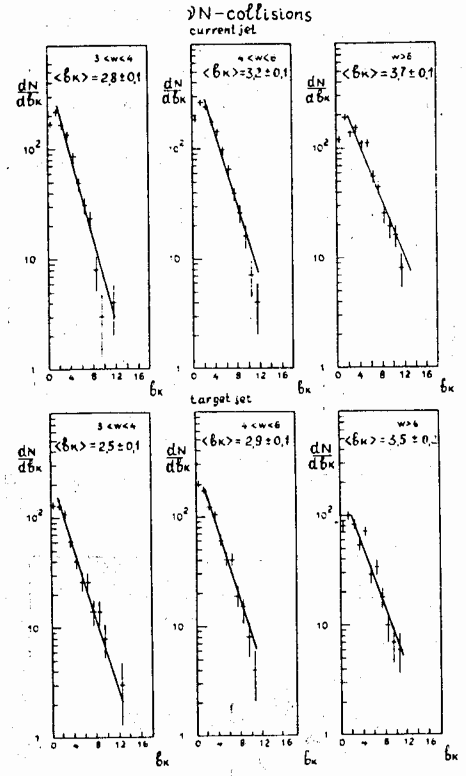


Fig.3

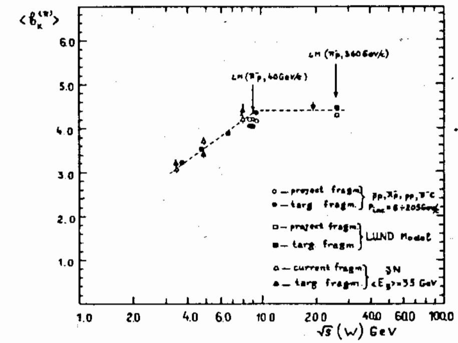


Fig.4

The existence of the asymptotic regime for hadron jets shows that this property is due to not the peculiarities of interaction of colliding objects but to a united mechanism of interaction between colour charge and QCD vacuum.

The observed universality of the properties of hadron jets and their invariance show evidence for the observability of colour charges and the possibility (by analogy with sort-lived particles) of studying their characteristics.

4. PROPERTIES OF NUCLEON CLUSTERS

As was mentioned above, the process of production of QGP appears at temperature around 200 MeV and low quark densities or at substantially lower temperature if the attainable densities are some times as large as the normal nuclear density. According to this statement it is natural to connect the separation of nucleon clusters in relativistic nucleus-nucleus collisions with the search for the states of highly excited nuclear matter including the search for a transition from hadronic matter to a plasma of deconfined quarks and gluons.

In the present paper nucleon clusters have been separated by analogy with case of hadron jets. For this purpose p, d, ^{4}He and ^{12}C collisions with ^{12}C nucleus at a momentum of 4.2·A·GeV/c were analysed[12].

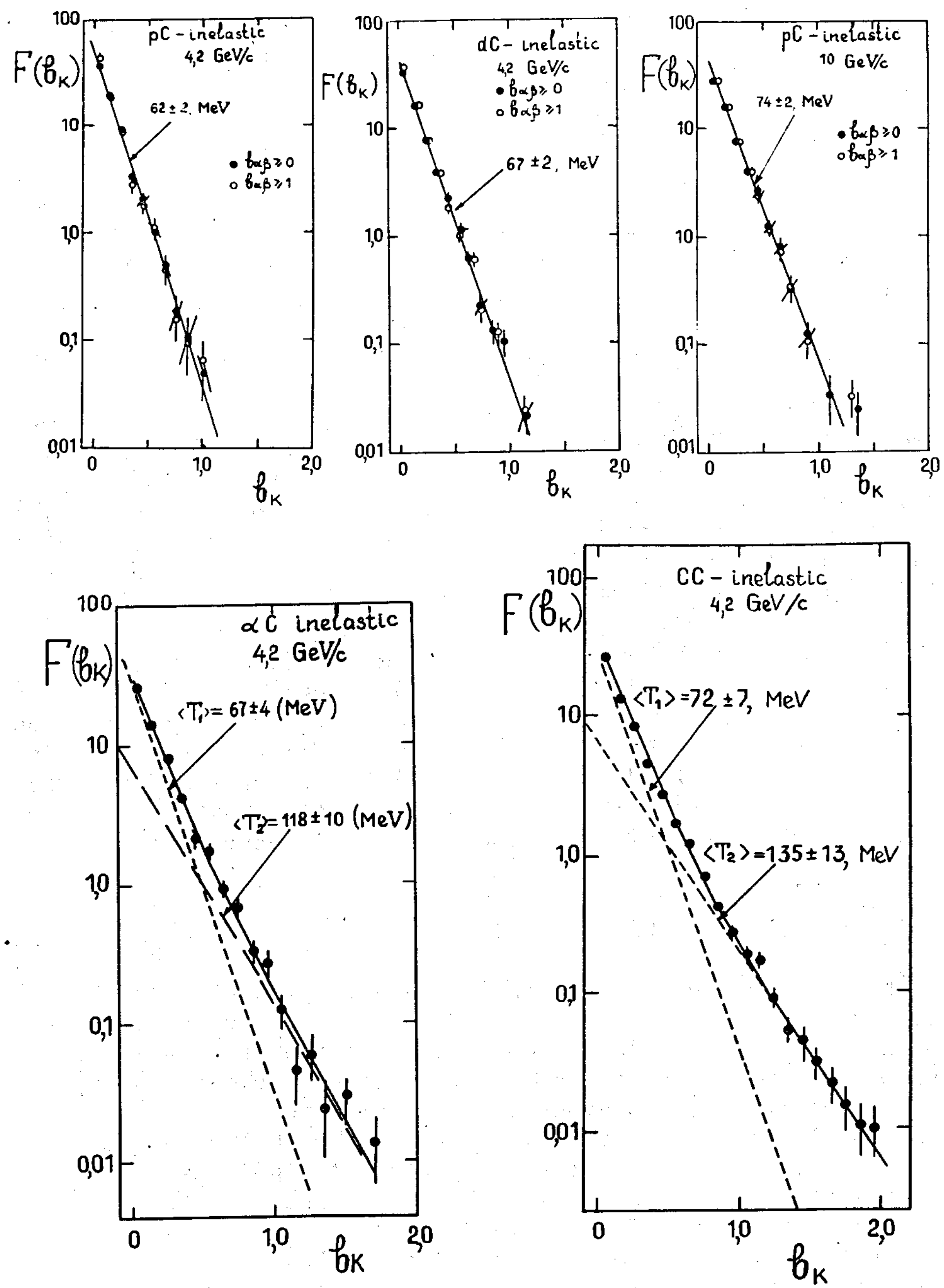


Fig.5

Invariant $F(b_k)$ distributions have been analysed to study nucleon cluster properties. Figures 5a,b present normalized functions $F(b_k)$ for nucleon clusters in (p, d, ^{4}He, ^{12}C)+^{12}C interactions. One can see that in the case of pC and dC collisions the functions $F(b_k)$ have exponential character and can be described by the following expression:

$$F(b_k) = a_1 \exp [-b_k/< b_k >].$$

In the case of ^{4}HeC and CC collisions the functions $F(b_k)$ can be approximated as a sum of two exponential dependences:

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

It is easy to show that the quantity b_k is unambiguously connected with the kinetic energy of particle in the clusters rest frame

$$b_k = \frac{2E_k}{m_k} - 2 = \frac{2T_k}{m_k},$$

where E_k and T_k are the total and kinetic energy of protons in the clusters rest frame. It follows that one can calculate the "temperature" of protons in clusters defining the values of parameters $< b_k >_1$ and $< b_k >_2$ by approximation. In our case the slope of invariant cross sections $\frac{1}{P}\frac{d\sigma}{dT}$ in the clusters rest frame was determined as follows $< b_k > = \frac{2<T_k>}{m_k}$.

The values of temperature obtained in this manner in different collisions are given in Figs.5a,b,c. One can see that clusters of two types are produced in the considered interactions: type I with $< T >_1 \approx$ 60-70 MeV is observed in all considered collisions and type II with $< T >_2 \approx$ 120-130 MeV is observed in ^{4}HeC and CC collisions. The contribution of the type II clusters is not large and in CC collisions is about (20±6)%.

The dependence of $< T >$ on proton multiplicity n_p is shown in Fig.6. One can see that the temperature of cluster grows with increasing n_p for all considered interactions. However, in pC, dC and ^{4}HeC collisions it is systematically lower than in CC ones at similar values of n_p. The maximum temperature in clusters in CC collisions reaches (120±4) MeV at n_p = 6. The appearance of high temperature clusters in CC collisions is connected with multinucleon interactions. The cross section of clusters with n_p = 5-7 is equal to 40 mb (~5% from all inelastic CC collision). Thus, multinucleon CC interactions are characterized by nuclear matter temperature being specific (according to theoretical consept 150-120 MeV) for the transition from hadronic matter to the QGP.

The presence of two different types of nucleon clusters in ^{4}HeC and ^{12}CC interactions, which existence is connected with different degrees of excitation of nuclear matter, is confirmed by the character of nucleon cluster distributions relative to target nucleus. The invariant functions $F(b_{IIC})$, describing cluster distributions relative to target nucleus for CC collision are given in Fig.7. On can see that the invariant $F(b_{IIC})$ distribution is well described by the sum of two exponential functions analogous to $F(b_k)$ function where the slope parameters $< b_{IIC} >_1$ and $< b_{IIC} >_2$ obtained by fitting correspond to $< b_{IIC} >_1 = 0.1 \pm 0.02$ and $< b_{IIC} >_2 = 0.51 \pm 0.05$. Within the experimental errors the value of $< b_{IIC} >_1$ coincides with the slope parameter $< b_{IIC} >_1 = 0.14 \pm 0.01$ of the function $F(b_{IIC})$ for pC collisions with nucleon cluster of type I only.

Thus, one can make a conclusion that the first slope of $F(b_{IIC})$ is connected with type I

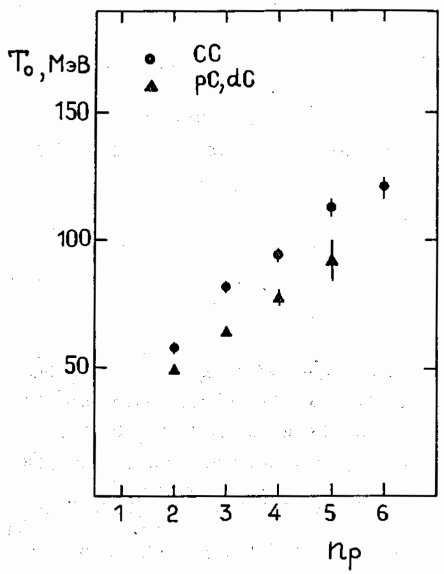


Fig.6

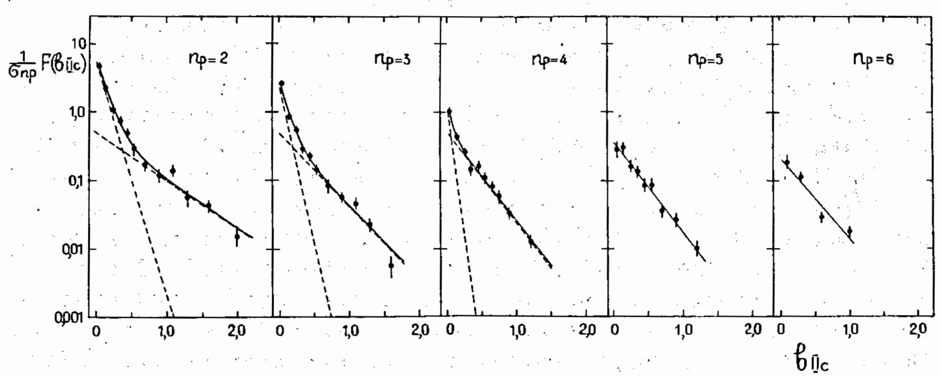


Fig.7

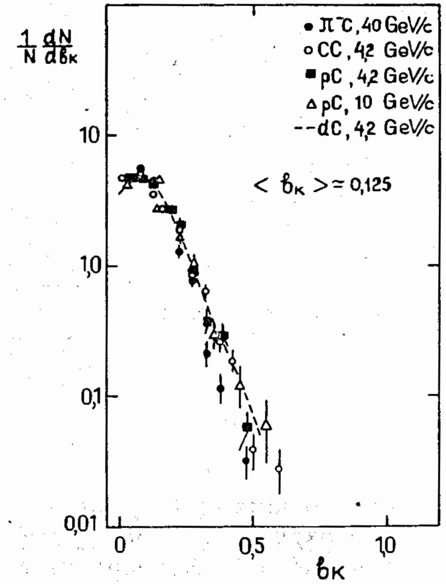


Fig.8

cluster production with $< T >_1$ = = 60-70 MeV and the contribution of these clusters decreases with growing of multiplicity n_p.

Figure 8 shows the $F(b_k)$ distributions of nucleon clusters of the type I for different kinds of nuclear reactions and energies. One can see that all distributions coincide with each other within experimental errors.

Universality of the properties of nucleon clusters with $< T_1 > \approx$ 60-70 MeV points out that we observe asymptotic state of excited nuclear matter in the transition domain of relativistic nuclear collisions [13].

5. INVESTIGATION OF A POSSIBILITY OF A QUASI-STATIONARY STATE PRODUCTION IN THE RELATIVISTIC NUCLEAR COLLISIONS

Independence of the properties of nucleon clusters with $< T_1 > \approx$ 60-70 MeV on the type of reaction points out that the process of cluster production characterizes fundamental properties of excited nuclear matter. In accordance with this, nucleon clusters seem to be decay products of some quasi-stationary multinucleon states. In such a case one can estimate the life-time of excited nuclear matter [14].

For this purpose the effective mass spectra of clusters have been analyzed. Figs.9 and 10 present the mass spectra of clusters M_{cl}, with multiplicity of protons n_p = 2 and 3 produced in interactions of p, d, ^{4}He and ^{12}C with carbon nuclei. As is shown above, clusters with small proton multiplicity are characterized mainly by low temperatures. From the figures one can see that the maxima, pointing to the possibility of production of nucleon resonance states are observed in dN/dM_{cl} distributions at some values of masses M_{cl}.

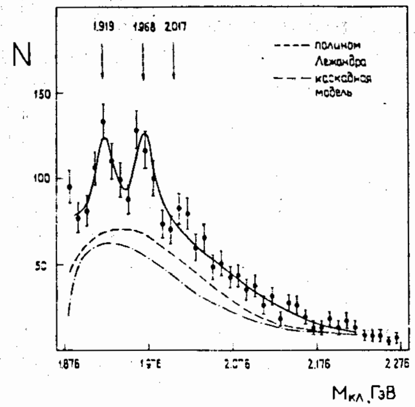


Fig.9

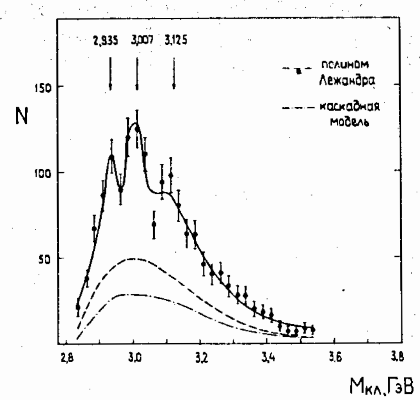


Fig.10

To determine the widths of possible resonances, the obtained spectra have been approximated by an expression consisting of the sum of the Breit-Wigner functions and a background term

$$F(M) = \sum_{i=1}^{3} \alpha_i \, BW(M) + kPh(M),$$

where α_i and k are the contributions of the Breit-Wigner functions and a background term.

In the considered mass intervals at $n_p = 2$ and 3 the mass resolution changes from 2-3 MeV at the phase space boundary up to 50 (at $n_p = 2$) - 100 (at $n_p = 3$) MeV. In this connection it is necessary to take into account the distribution of Breit-Wigner functions because of changing experimental errors in the measurement of M_{cl}.

The dependence $\sigma(m)$ obtained from the experiment has been satisfactorily described by a linear function.

The Breit-Wigner functions are given as

$$BW_i(M) = \frac{1}{(M_{oi} - m)^2 + \Gamma_i^2/4} .$$

The integral value of the Breit-Wigner functions taking into account resolution functions was normalized to unity.

Two variants have been considered as a background term:

(i) Background term was taken as Legendre polynomials of the third (at $n_p = 2$) and the forth ($n_p = 3$) degrees.

(ii) As a background distribution we assume an effective mass distribution obtained in pC, dC, ^{4}HeC and ^{12}CC collisions simulated by the cascade model with the aid of the algorithm used for the analysis of experimental data.

The results of approximation of the experimental spectra by the function F(M) are shown in Figs.9, 10 by solid lines. The Table presents both the values of masses M_i and widths Γ_i of the assumed resonances.

One can see from the Table that in two- and three-proton clusters the first two states with M_1 and M_2 are characterized by widths from some MeV up to some tens MeV, i.e. they are rather narrow.

Table

	$n_p = 2$		$n_p = 3$	
	M_i; GeV	Γ_i; GeV	M_i; GeV	Γ_i; GeV
1	1.919±0.003	0.023±0.012	2.935±0.011	0.071±0.020
2	1.967±0.004	0.010±0.015	3.007±0.006	0.016±0.015
3	2.017±0.042	0.168±0.084	3.125±0.029	0.249±0.045

The states with masses M_3 are characterized by widths of hundreds MeV. However, the mass resolution does not allow one to detect resonance states with widths of tens MeV in the region of large M_{cl}. That is why the observed states with masses M_3 can be really the supperposition of such states, and it will lead to increasing the measured width M_3.

Resonance structure could not be discovered in efective mass distributions of clusters with multiplicity $n_p \geq 4$ using the statistical data available at the present time.

Thus, the data obtained in our experiment show that in relativistic nuclear collisions the high excitation of nuclear matter is observed with the production of quasi-stationary nucleon states with $< T_1 > \approx 60$-70 MeV and a lifetime of $\sim 10^{-22}$ s.

The properties of this process do not depend on the type of reaction, and hence they reflect fundamental phenomena in relativistic nuclear physics.

6. CONCLUSIONS

The analysis of different relativistic 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 regularities:

(i) Universality of the properties of hadron jets in soft ($\pi^- p$, $\pi^- C$, pp, $\bar{p}p$) and hard ($\tilde{\nu}N$) interactions over an energy interval from 22.4 to 205 GeV has been observed. The asymptotic regime occurs at the energy in the c.m.s. $\sqrt{S} \gtrsim 6$ GeV (or at $E_q(E_{qq}) \gtrsim 3$ GeV).

This means that the hadronization of quarks, diquarks and other colour systems in soft and hard interactions depends neither on the origin nor on the properties of the colour quark system. This universality points to the fact that the hadronization of colour charges is determined by the dynamics of their interactions with QCD vacuum.

(ii) Established hadron jet properties (universality, independence of the type of reaction and relatrivistic invariance) make it possible to observe objects with colour charge and to determine quark and gluon properties.

(iii) Two types of 4-dimensional nucleon clusters characterized by different degrees of freedom of excited nuclear matter have been separated. The first type (type I) of clusters has the temperature $< T_1 > = (72\pm2)$ MeV and it is nearer to the parent target nucleus $< b_{IIC} >_1 = 0.14\pm0.02$ in the relative 4-velocity space; the second one (type II) has $< T_2 >=(135\pm13)$ MeV and more distant from the parent target nucleus $< b_{IIC} >_2 =$ $= 0.52\pm0.05$.

(iv) Universality of the properties of nucleon type I clusters has been observed in (π^-, p, d, ^{4}He, ^{12}C) + C collisions over an energy range 4 to 40 GeV. This fact should be considered as the generalization of the phenomenon known as "nuclear scaling".

(v) Observed properties (Universal character depending on neither the type of interactions nor the collision energy) of nucleon clusters are similar to those of quark jets but clusters are located in quite another region of kinematic variables as compared to hadron jets.

This results should be considered as exhibition of automodelity properties in the region of small b_{ik} (i.e. the existence of intermediate asymptotic regions on variable b_{ik} and independence in them of some invariant distributions in b_{IIC}: b_{IC}, $b_{\alpha\beta}$ and other large b_{ik} variables.

(vi) It was shown that nucleon clusters with $< T >_1 \approx$ ≈ 60-70 MeV produced in pC, dC, ^{4}HeC and ^{12}CC collisions at $P_{in} = 4.2 \cdot A \cdot$GeV/C can be interpreted as decay product of some multi-nucleon resonances with a lifetime of $\sim 10^{-22}$ s.

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