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E1-85-175

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DUBNA RESULTS IN THE REGION OF LIMITING NUCLEAR FRAGMENTATION

Invited talk at the XXII International Conference on High Energy Physics, Leipzig (DDR), July 19-25, 1984.

1985

The collision of high energy particles and relativistic nuclei with nuclei have recently become still more popular at the International Conferences on High Energy Physics.

Interest of studying such a type of collisions arises from the fact that under some definite conditions the relativistic nuclear interactions provide a unique possibility to investigate various aspects of strong interactions.

As recent studies have shown, the quark aspects of nuclear matter are of great importance for the construction of both the theory of strong interactions and modern nuclear theory. In particular, investigations of nuclear reactions with large momentum transfers in the region of limiting nuclear fragmentation have led to extremely important information on the role of quark-gluon degrees of freedom in nuclei.

Thus, studies in the field of relativistic nuclear physics are directly related to the problems of high energy and elementary particles being solved at the largest accelerator centres of the world.

Relativistic nuclear physics is of considerable importance in the Dubna research program. In particular, these studies are now a wide area activity at the Dubna synchrophasotron.

At present the synchrophasotron is the leading accelerator of light nuclei over an energy of up to 5 GeV per nucleon, which is in the region of limiting nuclear fragmentation and in which new properties of nuclear matter begin to manifest themselves.

Table I shows nuclear beams available at present at the Dubna synchrophasotron /1/. All these are external beams of fully stripped ions; fast and slow ejections are at the users choice. Cryogenic panels are being installed inside a part of the main ring of the synchrophasotron in order to improve the vacuum what is necessary for the acceleration of heavier (than in Table I) nuclei. All panels should be installed by the end of the next year. For $Z/A = 0.5$ nuclei the maximum kinetic energy is 4.2 GeV per nucleon ($P_{max} = 5 \cdot A$ GeV/c) what is substantially higher than at the Bevalac.

The total running time of the synchrophasotron is about 4000 hours a year, 85% of which is used to implement the program of experimental research.

A large number of physicists from JINR member-countries and other countries are involved in the program of relativistic nuclear physics at the synchrophasotron. Some aspects of this program are also being studied by Dubna physicists at the Serpukhov and CERN proton synchrotrons.

Results obtained have been published in many papers and were regularly presented at International Conferences /2-12/. Below we present a brief outline of the most significant physical results that have been recently obtained by different groups of JINR physicists.

Among different types of nuclear reactions at high energies of particular interest are those in the region of limiting nuclear fragmentation which is kinematically forbidden for one-nucleon collisions. A study of these reactions has led to the discovery of the cumulative effect and the most striking features of its.

Table I

Type of nuclei	Energy GeV	Intensity per pulse	Type of ion source	
p	9.0	4×10^{12}	duoplasmatron	
n	4.1	1×10^{10}	duoplasmatron	
d	8.2	1.5×10^{12}	duoplasmatron	
↑d (≈53% of the degree of polarization)	8.2	5×10^{8}	"Polaris"	
^{3}He	17.2	2×10^{10}	duoplasmatron	
^{4}He	16.4	5×10^{10}	duoplasmatron	
^{6}Li	24.6	1.5×10^{8}	laser	(10 joule
^{7}Li	23.9	2×10^{9}	laser	CO_2)
^{12}C	49.2	5×10^{8}	laser	
^{16}O	65.6	5×10^{7}	laser	
^{19}F	73.1	1.5×10^{7}	laser	
^{22}Ne	81.0	10^{4}	"Krion"	(electron beam)
^{24}Mg	98.4	10^{5}	laser	
^{28}Si	114.8	10^{3}	laser	

The hypothesis of the cumulative effect was first advanced by A.M.Baldin in 1971 /13/. The cumulative effect is the process of collisions between particles or nuclei and nuclei in the region of limiting nuclear fragmentation where scale invariance is valid. As a result of this, the momentum which is much larger than that per nucleon of relativistic nucleus is transferred to the particle produced.

Some important properties of the cumulative effect (such as scale invariance of inclusive spectra of pions and enhanced A-dependence of their production cross section) were found already in first experiments carried out by V.S.Stavinsky's group at the Dubna synchrophasotron with relativistic deuterons in 1971 /14/.

During the ensuing years some other consequences of the hypothesis of the cumulative effect have been confirmed experimentally by this team using beams of protons and deuterons with a momentum of 8.9 GeV/c and a large set (from D to U) of target-nuclei /15/.

The main results of these investigations are the following:

1. It has been found that the region of limiting nuclear fragmentation begins at an energy of 3.5 GeV per nucleon. In this case there is an asymptotic regime in which no dependence of the invariant cross section for a reaction of the type I + II → 1 + ... on the invariant specific energy of colliding objects and other parameters (except a scaling parameter) is observed. This result has been confirmed by experiments of other groups, which have studied cumulative processes for various types of reactions and over an energy range of up to 400 GeV /16 a-d/.

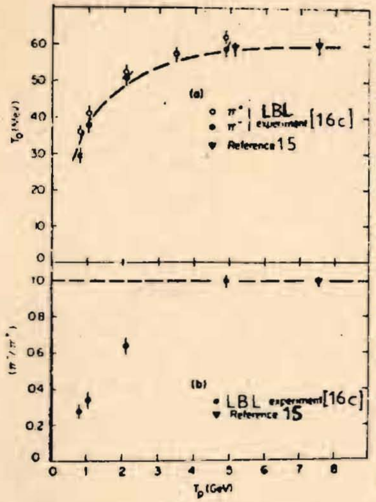

Fig. 1

Figs.1a and 1b show, as an example, the data (the energy dependence of the slope parameter T_0 on $E_1 \frac{d\sigma}{d\vec{p}_1} \sim \exp[-T/T_0]$ and the ratio $R = \pi^-/\pi^+$ for a Cu target) on cumulative $\pi^{\pm}$ production in pA collisions obtained in Dubna /15/ and Berkeley /16c/ experiments. Both are observed to rise with energy up to ~ 3-4 GeV after which levelling off occurs.

2. The cross sections for cumulative particle production in the region of limiting nuclear fragmentation ($4 \le E_{in} \le 400$ GeV) and in the range of scaling variable X from 0.6 to 3.5 are well approximated by a unique exponential dependence (see Fig.2a) $E_1 \frac{d\sigma}{d\vec{p}_1} = \text{const}\ A^{1/3} A^{m(X)} \exp[-X/\langle X\rangle]$,

where $\langle X\rangle = 0.14$ (to an accuracy of 10%) is a universal parameter which does not depend on the quantum numbers of cumulative particles; $m(X) = 2/3 + X/3$ for $0.6 < X < 1$ and $m(X) = 1$ for $X > 1$ and $A_{II} \geq 20$.

The variable X[17], closely related to the Bjorken variable $x = Q^2/2M\nu$, is defined as follows: $X = [(P_I P_I) - 1/2\, m^2] / [(P_I P_{II}) - M_I M_{II} - (P_{II} P_I)]$, where P_I and P_{II} are the four-momenta of colliding nuclei, M_I and M_{II} are their masses and the index corresponds to a secondary particle (in our case particle 1 is a pion). The variable X is called the effective cumulative number. In the rest frame of the fragmenting nucleus it is approximately equal to the minimum target mass $\beta_o = X = (E - P_{||})/m_N$, where E and $P_{||}$ are the energy and longitudinal momentum of the produced particle and m_N is the nucleon mass. For deep-inelastic lepton scattering, neglecting masses, X/A_{II} approaches x.

The cumulative region corresponds to $X > 1$.

Similar results and the same value of $\langle X \rangle$ have been confirmed in deep-inelastic muon scattering on nuclei (see Fig.2b). The corresponding prediction was made by A.M.Baldin[6,18] and realized in NA-4 experiments at CERN[19].

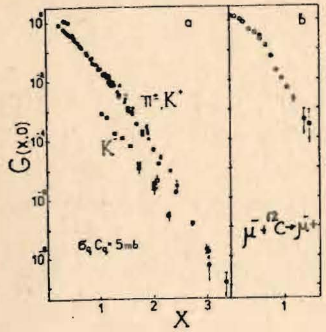

Fig. 2

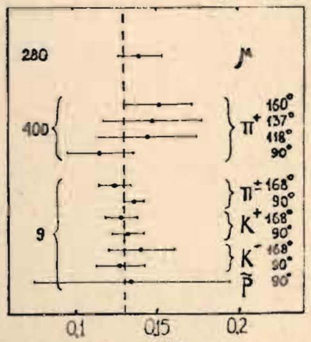

Fig. 3

Fig.3 compiles the values of $\langle X \rangle$ for different types of cumulative experiments including deep-inelastic scattering of negative muons on carbon nuclei for an energy of 280 GeV and momentum transfers of $Q^2 = -q^2 = 200\ (\text{GeV})^2$. As deep-inelastic lepton scattering is believed to represent interactions with quarks, results of the NA-4 experiments are very important to indicate the quark nature of cumulative processes.

3. For identical values of variable X the invariant cross sections of pion and kaon production obey the following approximate relation $E_1 \frac{d\sigma}{d\vec{p}_1}(\pi^+) \approx E_1 \frac{d\sigma}{d\vec{p}_1}(\pi^-) \approx E_1 \frac{d\sigma}{d\vec{p}_1}(K^+) \gg E_1 \frac{d\sigma}{d\vec{p}_1}(K^-)$. Such a fact can be interpreted as a result of pick-up from the symmetric quark sea of corresponding quarks by the valence quarks of the colliding objects (i.e., the valence quarks of the colliding objects form a part of $\pi^{\pm}$ and K^+, but they are not a part of K^- mesons). These results well confirm also the quark nature of the cumulative effect.

Thus, one can assume that the invariant cross section of the process I + II 1 + ... in the region of limiting fragmentation, for example, of the nucleus II is of the form $E_1 \frac{d\sigma}{d\vec{p}_1} = C_q^1 \sigma_q^1 G_{II/q}(X, P_\perp^2)$. Here $G_{II/q}$ is the quark-parton structure function of nucleus II, C_q^1 is the constant characterizing the hadronization of quark into hadron 1, σ_q^1 is the cross section of the process where quark q from hadron II passes through target I having the avoided collision. The physical meaning of the functions $G_{II/q}$ are universal momentum distributions of quark q in nucleus II.

4. The most striking feature of the cumulative effect is the universal (for all the nuclei) X dependence of $G_{II/q}$. In the range $X > 1$ the function $G_{II/q}$ is well approximated by a simple dependence $G_{II/q} \sim \exp[-X/\langle X \rangle]$ with the slope parameter $\langle X \rangle = 0.14$. As can be seen from Fig.2, $G_{II/q}$ is different from zero for X up to 3.5. In this case the properties of $G_{II/q}(X)$ are in good agreement with the idea of the cumulative effect as a result of interactions of multiquark configurations existing in the nucleus and containing an effective number of nucleons equal to X.

In accordance with the approximation of the limiting fragmentation cross section $\sigma_{II} = E_1 \frac{d\sigma}{d\vec{p}_1} \sim G_{II/q}(X, P_\perp^2)$, the ratios of structure functions for different nuclei (in this case He, Al and Pb) normalized to nucleon have the following X dependence:

(i) $\sigma_{II'}/\sigma_{II} = A_{II} G_{II'/q} / A_{II'} G_{II/q} < 1$ for $A_{II'} > A_{II}$ and $X < 1$;

(ii) $\sigma_{II'}/\sigma_{II} \gtrsim 1$ for $X > 1$ (see Fig.4). Such their very different behaviour can be interpreted as a manifestation of multiquark configurations existing in nuclei. In our case, in the D nucleus, there are no configurations including quarks from more than two nucleons, while the Al nucleus differs a little, in this sense, from the Pb nucleus.

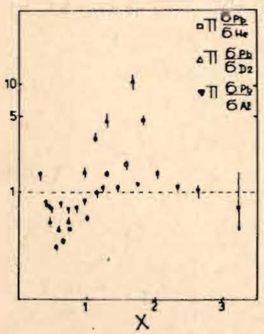

Fig. 4

These results have been in part confirmed by experiments on deep-inelastic scattering of muons at CERN[20] and electrons at SLAC[21] on D and Fe nuclei. This is often called the "EMC effect". However, the data of these experiments are restricted only to the region $X < 1$.

Dubna results give additional information on the properties of $G_{II/q}$ for the region $X > 1$ which have not yet been studied in lepton-nucleus interactions, and they can be considered as a prediction. In particular, the investigation of the A dependence of cumulative pion production at $X = 1.3$ for more than twenty nuclei shows (see Fig.5a) that the multiquark configurations differ from one another for all nuclei with $A_{II} \leq 20$, and for $A_{II} > 20$ the amount of multiquark configurations in nuclei is stabilized at a certain level. A similar A dependence of cumulative pion production at $X = 2.1$ (see Fig.5b) makes it possible to separate the contribution of "9q" and "12q" states to the structure functions $G_{II/q}$ of nuclei.

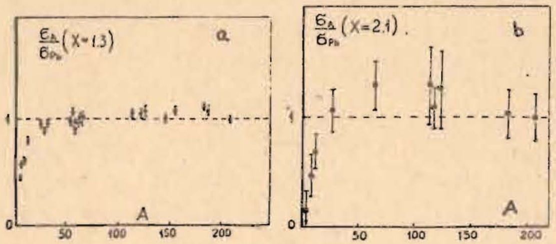

Fig. 5

Thus, an experimental test of the hypothesis of the cumulative effect carried out in systematic investigations of inclusive nuclear reactions with large momentum transfers in the region of limiting nuclear fragmentation confirmed the existence of this physics phenomenon, established the universality of its main properties and its quark nature. The regularities which follow from these experimental data on limiting nuclear fragmentation show evidence for the quark-parton structure functions of nuclei as independent (irreducible to one-nucleon) objects of hadron physics. The properties of these functions are in good agreement with the idea that in the nucleus there are multiquark states realized by a group of nucleons inside the nucleus with effective number X which are substantially distinct from multinucleon systems in a free state. The above properties of the structure functions of nuclei, which have been recently confirmed in part by experiments on deep-inelastic scattering of leptons on nuclei, enable one to predict results of future similar experiments.

An attempt to study cumulative processes in other than inclusive experiments have been carried out by several groups from the High Energy Laboratory of JINR using pictures from the 2m propane

bubble chamber with Ta plates, This technique enables one to investigate inelastic processes under 4π-geometry conditions and, in consequence, to obtain more extensive information on the dynamics of cumulative interactions.

Below we shall discuss results of a study of multiple particle processes in pC, pTa (at 10 GeV/c) and $\pi^- C$ (at 40 GeV/c) collisions accompanying the production of cumulative hadrons.

Available experimental data have been analysed versus the largest value of cumulative number $\beta_o = \sum_i \beta_i$, where $\beta_i = (E_i - P_{i\,||})/m_N$, among all the values of β_i for secondary hadrons (in our case $\pi^{\pm}$, p and so on) in each event considered. The quantity β_o thus determined is an ordinary variable of parton models related to one nucleon of the nucleus. For example, selecting interactions having particles with $\beta_o > 1$ (as known, cumulative), we select events in which there occurred the hard interaction of constituents of colliding objects.

The selection criterion for cumulative interactions can be extended. The point is that a fast quark produced in the hard interaction can be hadronized not only to a cumulative particle (version I) but also to a cumulative jet (version II).

In accordance with the aim indicated, both versions of the approach to a study of different kinds of correlation phenomena are used in analysis of the experimental data of both pC, pTa and $\pi^- C$ interactions.

In version I the properties of general average characteristics (multiplicities, momenta and emission angles in the lab.system, rapidities in the c.m.s. of the hadron-nucleon) of pions and protons produced in the above hadron-nucleus interactions have been analysed versus β_o. It has been found /22/ that the values of $\beta_o = 0.4$ (for pions) and $\beta_o = 1.2$ (for protons) are the boundaries on which there change the regimes of all characteristics of multiple particle production on nuclei. The obtained results indicate the existence of two mechanisms at least which are responsible for the production of secondary $\pi^{\pm}$ and p in these collisions. It has been found that the region of cumulative interactions with $\beta_o \geq 0.4$ (for $\pi^{\pm}$) and $\beta_o \geq 1.2$ (for p) is distinctly singled out for all the studied properties.

The analysis of the events from the cumulative region has shown the following: (i) The processes, which led to cumulative pion production, are independent of the processes of cumulative proton production (only in $\sim 12\%$ of the events proton cumulative processes are accompanied by the emission of cumulative mesons, and this fraction does not depend on β_o).

(ii) The invariant inclusive cross sections for cumulative $\pi^{\pm}$ and p versus variable $Q = \beta_i - B$ (here B is the baryon number of hadrons) have an exponential form $\sim \exp[-\beta_i / \langle\beta_i\rangle]$ with $\langle\beta_i\rangle_{\pi^{\pm}} = 0.143 \pm 0.004$ and $\langle\beta_i\rangle_p = 0.130 \pm 0.005$ (i.e., with universal slope parameter $\langle X\rangle = 0.14$). It should be noted that this dependence has been also observed in the cumulative production of jets/23/. (iii) The behaviour of leading $\pi^{\pm}$ mesons (i.e., the pions having $x = P^*_{\parallel} / P_{max} > 2$ in the NN c.m.s.) accompanying the production of cumulative hadrons is also of interest. Their general average characteristics appear to be independent both of β_o and β_i, i.e., they do not "feel" the cumulative effect. It is difficult to explain these facts in the framework of the models based on the notions of "central" collisions in which the leading effect should be suppressed. On the other hand, it is difficult to understand this effect using the models of rescattering and collision of incident hadron with nucleon having large fermion momentum. The "leading" effect is in good agreement with the fact that leading hadrons are produced from spectator quarks, which pass through the nucleus without interaction, and cumulative particles are the result of hard interactions of another quark of incident hadron.

All the above general characteristics of secondary particles produced in pC, pTa collisions at 10 GeV/c and π^- C interactions at 40 GeV/c have been also observed for proton production in pion-nucleus interactions at momenta of 3.7, 6 and 9 GeV/c/24/ in γ + nucleus collisions/25/ and in $\nu/\bar{\nu}$ + nucleus interactions/26/. All these facts confirm the universality of the general characteristics for the processes of cumulative hadron and accompanying particle production in various nuclear interactions at different energies of colliding objects.

The production of hadron jets in cumulative processes for π^- C interactions at 40 GeV/c has been studied/23/ in version II. Quark hadronization from multiquark nuclear states is practically unstudied. Therefore it is particularly interesting to select jets in the region of nuclear fragmentation and to compare them with the properties of hadron jets in e^+e^- and soft hadron-hadron collisions.

The analysis of the available data was performed in the c.m.s. of incident pions and the corresponding number of nucleons (ν_n) involved in the interaction. The energy of collision is defined by the formula $E_{c.m.s.} \equiv \sqrt{S} = \sqrt{\nu_n m_N E_{\pi^-}}$.

Such an approach makes it possible to observe the change of the properties of hadron jets, produced on nuclei, with the number of nucleons involved in the interaction what is somewhat similar to an investigation of the properties of hadron jets versus the atomic number of target-nucleus. Multinucleon π^- C interactions with the total charge of secondary particles $Q = N_+ - N_- \geq +1$, where N_+ and N_- are the numbers of secondary positive and negative particles per interaction, were selected for the analysis (in this case the protons having $P_{lab} \leq 300$ MeV/c were excluded).

The cumulative events were selected using the variable $\beta_o = \sum \beta_i > 1.0$. In this case summation was done over all secondary particles moving backward in the $\pi^-\nu_n$ c.m.s. because the hadronization of quarks from multiquark states can occur so that none of the particles has the β_i outside the kinematical limit of pion-nucleon collisions, whereas the sum of all β_i in a jet produced in quark hadronization is larger than 1.0. A group of particles satisfying the condition $\beta_o > 1.0$ and having $|x_i| = 2|P^*_{i\parallel}| / E_{c.m.s.} \geq 0.05$ was assumed to be a cumulative jet.

Based on the analysis performed, the following main conclusions can be drawn: (i) In cumulative π^-C interactions with the number of interacting nucleons $\nu_n \leq 5$ the production of hadron jets is observed that collimated towards an incident pion and in an opposite direction in the $\pi^-\nu_n$ c.m.s. The values of average sphericity ($\langle S\rangle$) for both jets coincide with the data for e^+e^- and hadron-hadron interactions at equal $E_{c.m.s.}$ (see Fig.6). (ii) In π^-C interactions the longitudinal and transverse (Fig.7) momentum distributions of pions for cumulative jets and also for the jets collimated towards an incident pion agree with similar distributions of pions in e^+e^- annihilation. In this case the longitudinal momentum distributions of pions, calculated in the rest frame of a meson system ($\langle M_o\rangle = 10$ GeV) **that is identical** to e^+e^- events, were analysed. (iii) Within the experimental errors, the average multiplicity of charged hadrons ($\langle n_{ch}\rangle$) in cumulative π^-C interactions is in agreement with the multiplicity in e^+e^- annihilation for equal $E_{c.m.s.}$. (iv) The quark fragmentation functions $F_q(x_E)$ for K°-mesons and Λ^o-hyperons in cumulative π^-C, e^+e^- and soft π^-P collisions have a similar x_E dependence (see Figs.8a,b). In this case the $\langle n_{K^o}\rangle$ and $\langle n_{\Lambda^o}\rangle$, produced in quark fragmentation due to the pickup of strange quarks from the sea, coincide in these interactions. (v) The diquark fragmentation functions $F_{qq}(x_E)$ for K°-mesons and Λ^o hyperons from multiquark states of the target-nucleus are consistent with similar π^-P and e^+e^- data (see Figs.9a,b). In this case the functions $F_{qq}^{K^o}(x_E)$ in cumulative $\pi^- C$ and $F_{qq}^{K^o}(x_E)$ in e^+e^- collisions are similar over the range $x_E \lesssim 0.4$.

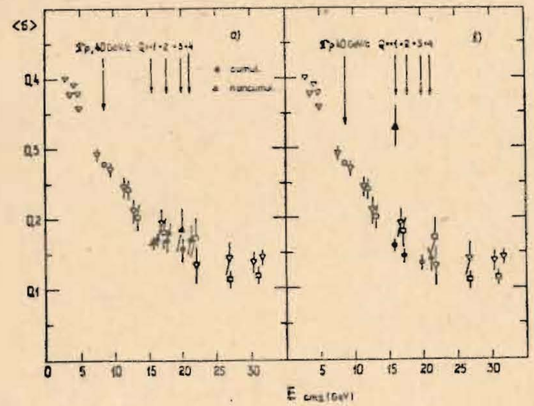

Fig. 6

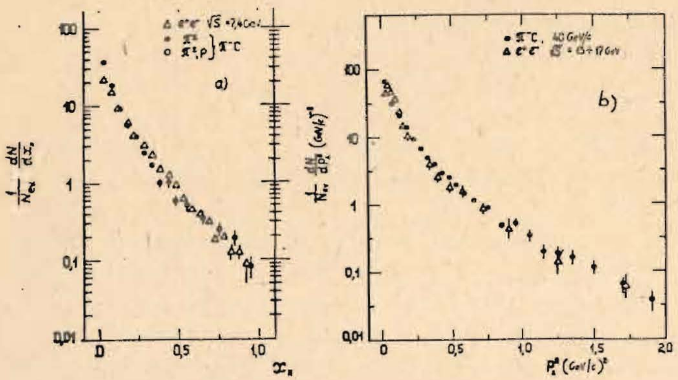

Fig. 7

Thus the results obtained in the study of jet production in $\pi^- C$ interactions at 40 GeV/c indicate that the quark and diquark fragmentation into pions and strange particles is universal in cumulative collisions on light nuclei, soft hadron collisions and e^+e^- annihilation.

The fragmentation of multiquark states on light nuclei is similar to that of quarks and diquarks in soft and hard collisions of particles.

The above data on the study of the cumulative effect allowed us to broaden ideas of the quark nature of nuclear matter. The observation of multiquark states should be also expected in processes involving relativistic nuclei.

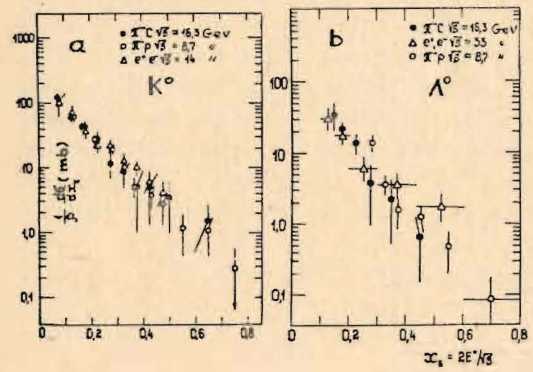

Fig. 8

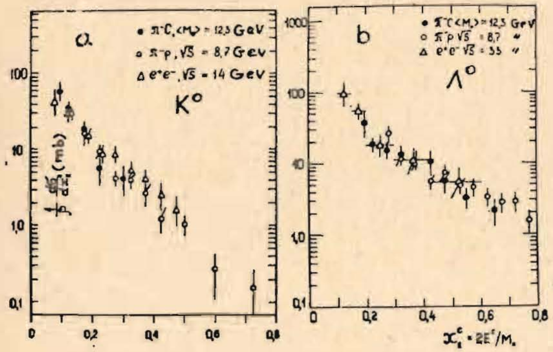

Fig. 9

Such a kind of experiments has been performed by the groups of L.S. Azhgirey and L.N.Strunov in studies of inelastic scattering processes of deuterons on different nuclei in reactions of the type $d + A \to p/d + X$ with relatively large momentum transfers.

The spectrum of deuterons emitted at an angle of 139 mrad in dd interactions at 9 GeV/c was studied by L.S.Azhgirey's group/27/ (fig.10). From the figure one can see that a peak from elastic dd scattering at 8.59 GeV/c is seen in the spectrum. The structure over a momentum range of 7.9-8.6 GeV/c caused by quasi-elastic dd scattering, occurring with target deuteron break-up but without the production of new particles, is also seen in the spectrum. This part of the spectrum is well described within the framework of the multiple scattering model. An analysis of the deuteron spectrum in a momentum region of < 7.9 GeV/c shows that the processes of coherent pion production, when the incident deuterons are not broken, proceed at momentum transfers of < 1.5 $(GeV/c)^2$ with a marked probability. This fact may be considered as an indication of the admixture of "6q" configurations in the deuteron. In particular, in order to describe the above results, it was necessary to introduce the "hybrid" wave function of deuterons containing about 5% of "6q" states/28/.

A similar experiment, performed by L.N.Strunov's group[29] with a high-resolution magnetic spectrometer "Alpha" (reaction d + C (or CH_2) → p + X at 8.9 GeV/c), allowed one to reach higher momentum transfers and to reveal a discrepancy with the standard nucleon-nucleon interaction form (the "Paris" potential) as seen in Fig.11. The "Dubna wave function" extracted from these data agrees with that from electroproduction experiments at SLAC[30] and Saclay[32]. The observed excess for $k \geq 0.2$ GeV/c (k is a relative nucleon momentum in the deuteron) is interpreted as a manifestation of the "6q" component in the deuteron wave function: $\psi(d) = (1-\alpha)\,\psi(pn) + \alpha \cdot \psi(6q)$, with a "6q" admixture of about 10%. The hybrid model[33] has been used to describe the data.

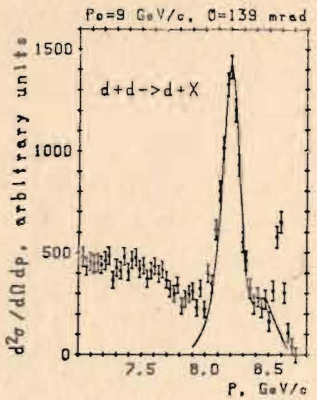

Fig.10

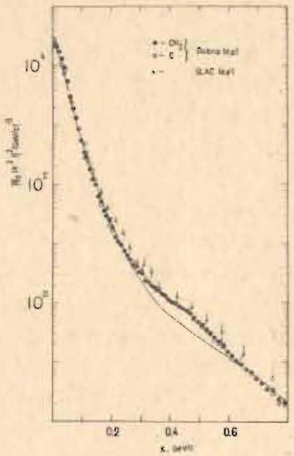

Fig. 11

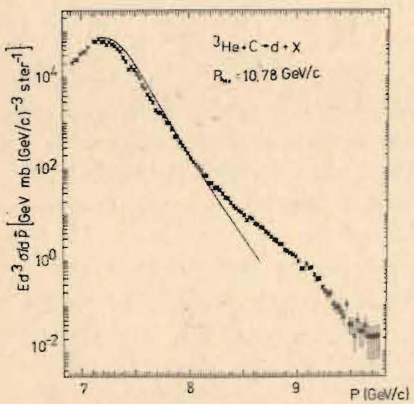

Fig. 12

The "Alpha" team has also begun to investigate $^3He \rightarrow p$ and $^3He \rightarrow d$ reactions at a beam momentum of 6.0-13.5 GeV/c in order to extract the ^3He wave function, particularly at a higher value of internal momentum. Preliminary data on the cross section of $^3He \rightarrow d$ fragmentation and the calculated results using the solution of the Faddeev equation and the NN potential with a soft core[34] can be seen in Fig. 12. A discrepancy between the experimental data and the model is again observed here.

An investigation of the fragmentation of polarized deuterons could give additional information on the quark structure of the deuteron wave function[35]. Such an investigation is planned at the Dubna synchrophasotron.

Turning now to the second topic, which is multiple particle production in relativistic nuclear collisions (the range of small Δy and small momentum transfers), I would like to point out that the relevant experimental data have been obtained at Dubna as well as at Berkeley.

Collisions of such a type make a decisive contribution to the total cross section and are well described in the framework of ordinary nuclear physics where the nucleon is a "good" quasi-particle even at the highest energies. Relativistic nuclear collision processes are described in the same way as usual multiple particle production processes of hadron physics on the basis of average general characteristics.

In particular, the study of multiple particle production processes in nucleus-nucleus collisions has led us to the conclusion that the main characteristics of these processes can be described as a superposition of basic characteristics for nucleon-nucleon collisions. In this case one can say that the additive nucleon model works well. The validity of this fact follows due to small momentum transfers in these processes that make a major contribution to the total cross section.

By the present time a general picture of the relativistic nuclear collisions is to a large extent clarified. Although the range of small Δy and small momentum transfers yields no essentially new information even at the highest energies, a study of multiple particle production in nucleus-nucleus collisions is very important for the solution of many problems of relativistic nuclear physics and many problems of astrophysics.

Multiple particle production has been studied at Dubna by means of nuclear emulsions, bubble and streamer chambers.

An interesting question in nucleus-nucleus collisions is how many nucleons participate in the interaction (ν_n).

Table II shows some new results[36a] on average numbers of participant protons ($\langle n_p \rangle$) and correlated average numbers of participant nucleons ($\langle \nu_n \rangle$) for interactions between d, ^4He, ^{12}C and C, Ta at 4.2 GeV/c per nucleon. In the table are also given average numbers of proton participants ($\langle n_p \rangle^{DCM}$) obtained from the DCM model/36b/. It can be seen that the experimental data make it possible to choose classes of interactions with the number ν_n varying over a wide range. However, the theoretical values for $\langle n_p \rangle^{DCM}$ are slightly greater than the experimental ones. Perhaps the DCM model slightly overestimates the number of cascade rescatterings of secondary particles.

Table II

Type of interactions	dC	^{4}HeC	CC	CC central	dTa	^{4}HeTa	CTa	CTa central
$\langle n_p \rangle$	2.40 ±0.03	3.27 ±0.05	5.11 ±0.08	8.35 ±0.06	5.52 ±0.12	8.64 ±0.24	13.84 ±0.37	29.96 ±0.55
$\langle \nu_n \rangle$	4.4 ±0.1	6.2 ±0.2	10.2 ±0.2	16.0 ±0.5	11.2 ±0.3	17.4 ±0.5	28.5 ±0.8	61.4 ±1.2
$\langle n_p \rangle^{DCM}$	-	-	-	8.7	-	-	14.9	32.8

Let us look at some new results on interactions between p, d, ^{4}He, ^{12}C and carbon/36a/. These reactions were studied by a group of the 2m propane bubble chamber. Table III shows the average general characteristics of secondary π^--mesons together with the predictions of a Dubna version of the cascade model (DCM)/36b/. From the table one can see a good agreement of the experimental data with the model.

Table III

		pC	dC	^{4}HeC	CC
$\langle n_- \rangle$		0.33 ± .02	0.62 ± .03	1.07 ± .05	1.52 ± .07
$\langle n_- \rangle$	expt.	1.14 ± .08	1.23 ± .08	1.11 ± .08	0.85 ± .07
D_-^2	DCM	1.23	1.15	1.07	0.70
$\langle p_\perp \rangle$	expt.	0.26 ± .01	0.26 ± .01	0.26 ± .01	0.25 ± .01
GeV/c	DCM	0.21	0.23	0.24	0.24
$\langle y_{lab} \rangle$	expt.	0.85 ± .04	1.00 ± .03	1.04 ± .03	1.10 ± .03
	DCM	0.95	0.98	1.05	1.05

Fig. 13 displays the dependence of the average number of π° ver-

sus the number of π^--mesons for dTa and CTa collisions at 4.2 GeV/c per nucleon/37/. Contrary to nucleon-nucleon data at the same energy per nucleon (where the average number of π°-mesons decreases with increasing the number of π^--mesons), in nucleus-nucleus collisions $\langle n_{\pi^\circ} \rangle$ increases with $\langle n_{\pi^-} \rangle$. This difference in behaviour is probably only to reflect the mechanism of multiple NN collisions in nucleus-nucleus interactions.

The first results on antideuteron-deuteron interactions have been submitted to this Conference by the "Ludmila" collaboration/38/. The data (~6500 events of $\tilde{d}$d interactions) were obtained by means of a track sensitive deuteron target (100 x 16 x 8 cm^3) situated inside the 2m hydrogen bubble chamber exposed to an RF separated 12 GeV/c antideuteron beam (~0.5 $\tilde{d}$ per pulse and hadronic background ~30%) at the Serpukhov accelerator.

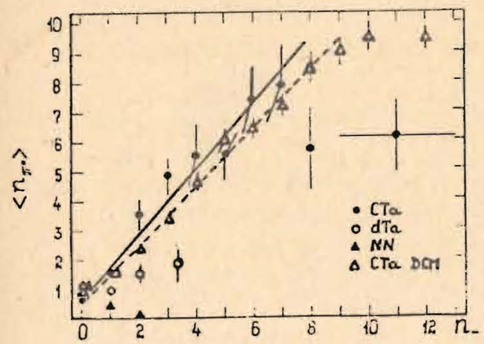

Fig. 13

The total $\tilde{d}$d annihilation cross section at 12 GeV/c was estimated to be larger than 0.04 mb based on one 10-prong event (see fig.14) with no charged baryons or antibaryons and a missing mass of $2m_N$ found in a part of the data. The multiplicity distribution of charged particles in $\tilde{d}$d interactions was determined with $\langle n_{ch} \rangle = 4.67 \pm 0.05$ and $\langle n \rangle/D = 2.20 \pm 0.04$, while for $\tilde{d}$d multinucleon interactions $\langle n_{ch} \rangle$ and $\langle n \rangle/D$ were estimated to be ~30% larger.

This team also studied the reaction $\tilde{d}p \to \tilde{p}p\tilde{n}$ at 12 GeV/c /38/. The differential and total (10.4±0.7 mb) cross sections were determined on the basis of 630 events from this reaction. The experimental data were found to be in agreement with the theoretical predictions obtained in terms of Glauber formalism.

The events with $\tilde{p}$ spectator were further selected allowing one to study $\tilde{n}p$ interactions at 6 GeV/c. Approximately 250 events of $\tilde{n}p$ elastic scattering were selected giving σ_{el} (13.9±1.5 mb) and $d\sigma_{el}/dt$ (the slope parameter b = 12.7±1.3 (GeV/c)$^{-2}$) close to the corresponding quantities for $\tilde{p}p$ elastic scattering data at the same energy. It should be noted that the $\tilde{p}n$ data at close energy yield smaller values of the slope parameter/39/. Such a discrepancy arises probably due to methodical difficulties connected with the selection in the experiments with the deuteron target.

Passing on to another topic, which is the charge-exchange process with Δ -isobar excitation in the nucleus, I would like to point out that this process may be the most suitable to solve the problem of the excitation of Δ -isobar degrees of freedom in nuclei and to study the properties of the Δ in nuclear matter.

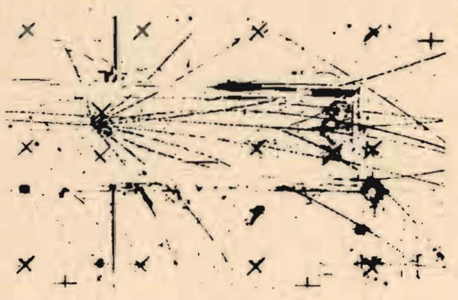

Fig. 14

Measurements of the invariant cross sections of the $(^3He, t)$ reaction on C and CH_2 targets at triton emission angles of $\leqslant 0.4°$ were performed at an incident momentum of 4.37, 6.78 and 10.78 GeV/c (see Fig.15). The statistical uncertainty of the data does not exceed 5%, the normalization one is less than 10%.

The results can be summarized as follows: (i) A single peak is seen in the $p(^3He, t)$ reaction cross section (black circles in Fig. 15). The position and width of the peak are close to the expected ones for the $p(^3He, t)\Delta^{++}$ reaction. There are two peaks in the $C(^3He, t)$ cross sections (open circles in Fig. 15). The first one is located at small Q, and the peak height decreases with increasing projectile energy. The second peak is located in the same Q region ($Q = T_{^3He} - T_t$ and T is kinetic energy) as the peak in the $p(^3He,t)\Delta^{++}$ reaction cross section. (ii) Two mechanisms contribute to the reaction investigated. One of them (the first peak in the $C(^3He, t)$ reaction) corresponds to spin-isospin excitations of nuclear levels in the residual nucleus. The other one contributes to an internal excitation of target-constituent nucleons (in this case we shall refer to it as to Δ production). The contribution of the latter mechanism increases with increasing momentum and dominates at the largest momentum used. (iii) The ratio of the charge-exchange cross section $d\sigma/d\Omega(0)=\int_{Q\geqslant 75\,MeV} d^2\sigma/dp\,d\Omega$ for C and H increases with increasing incident momentum varying from -0.5 at 3.9 GeV/c to ~ 1.6 at 4.37 GeV/c and 2.3 at $P_{in} \geqslant 6.78$ GeV/c (in this case the contribution of the tail from the nuclear excitation peak being subtracted). (iv) There is a shift between the Δ -peak positions in the reaction on C and H at fixed incident energies. This shift can be due to

a kinematical difference between the minimal longitudinal momentum transfer (at fixed Q) required to excite the Δ collectively on a few-nucleon group in ^{12}C and the one in the charge-exchange process on a single nucleon. (v) The comparison of the data on absolute $(^3He, t)$ cross sections on H and ^{12}C, as well as the Glauber calculation results, shows that in the charge-exchange reaction with Δ production in nuclei at high energies such mechanisms of the collective type are essential, which cannot be reduced to Δ production on a single target-constituent nucleon.

Thus, these results are rather unexpected from the point of view of "standard" models if one neglects those collective-type effects which cannot be reduced to simple "one-nucleon" mechanisms and also does not take into account possible changes of the properties of the Δ passing through nuclear matter.

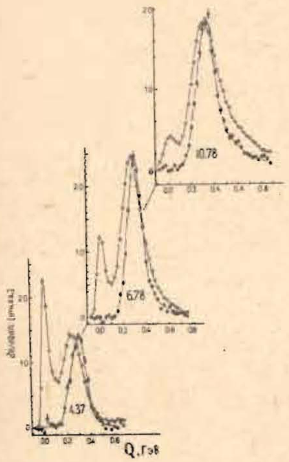

Fig. 15

Concluding this part of my talk, I would like to say that fragmentation and particle production processes in collisions of relativistic nuclei are perhaps "ordinary nuclear physics in a fast-moving reference frame" only at small momentum transfers and small Δy, while at large momentum transfers they reflect the quark structure of nuclei.

The Dubna results have been obtained on the properties of nuclear reactions at small momentum transfers and small internucleon distances that allowed one to clarify a general picture of the dynamics of these processes fairly completely.

Of special interest are, in our opinion, the investigations using the nucleus as a laboratory for "exotic phenomena". In connection with this topic, I would like to make some comments on "anomalons", which have attracted large attention during the last few years, and the search for manifestations of a phase transition of hadron matter to a quark-gluon plasma.

First of all, let us look at some new results on "anomalons". In a large number of papers devoted to the study of inelastic nuclear collisions for high energies the effect of anomalous increasing interaction cross sections for secondary stripping fragments having charge $Z \geqslant 2$ of projectiles with target-nucleus has been reported. This information has aroused considerable interest because this effect can be directly associated with a possible existence of excited fragments with an anomalously large cross section and a lifetime of $\sim 10^{-10}$ s. Now it seems that the odds are against the existence of these phenomena: one can quote here several recent experiments using emulsions/41, 42/, plastic detectors/43/ and multilayer Cherenkov counters/44,45/. In particular, I show in Fig.16 new results of the Dubna emulsion collaboration/41,42/. The problem of anomalons has been investigated on 6053 secondary interactions of projectile nucleus fragments with charges from 3 to 10 found in the nuclear photoemulsion exposed to a ^{22}Ne beam at 4.1 GeV/c per nucleon. From the figure one can see that the data, in which statistics was high enough to allow fragments of all charges from Z = 3 to Z = 10 to be studied separately, do not exhibit any significant variation of interaction mean free path (λ, Λ) measured at different distances from the point of projectile fragments (X). The boundary of the region of stable anomalon existence allowed by this statistics is estimated at a 1% coexistence level by the method of maximum likelihood.

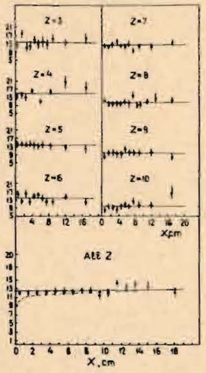

Fig. 16

Similar results have been obtained in a high-statistics electronics experiment using a live target of 40 Cherenkov counters with thin solid radiators (5 mm of plexiglass) which make it possible to measure the fragment charge and the coordinates of the point of its creation and absorption. The experiment/45/ was performed on a Mg beam at 4.5 GeV/c per nucleon. The admixture of ^{12}C nuclei in the beam was used for detector calibration. The branching of the nuclear reaction channels and the mean free path for different fragments are in reasonable agreement with the published data/43,44/(see Table IV).

Table IV

	Mg	Na	Ne	F
Mean free path (mm)	126±2	236±5	133±3	134±5
Branching ratio		0.108±0.004	0.095±0.004	0.052±0.003

The experimental result shows (see Fig.17) that the abundance of anomalons with a mean free path of 0.7-2.0 cm is less than 2% for Na, Ne and F fragments ($9 \leq Z \leq 11$) created by the interaction between Mg and light nuclei contained in the plexiglass target ($C_5H_8O_2$, density ρ = 1.16 g/cm^3).

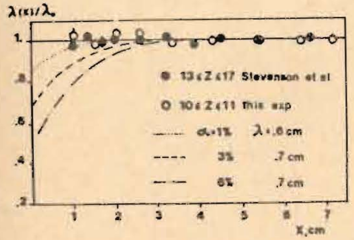

Fig. 17

Coming now to the second topic, I would like to tell very briefly about results of an investigation/46/ of the temperature and density of nuclear matter in "central" ^{12}C + ^{12}C collisions at 4.3 GeV/c per nucleon. For CC central interactions (i.e., the events with no more than two positive, singly-charged particles having momenta $P_{lab} \geq 3$ GeV/c and emitted at $\Theta_{lab} < 4°$ with respect to the beam direction) with additional selection $P_{\perp} \geq 500$ MeV/c, the root-mean-square radius $r_{rms}(pp)$ = = (2.6±0.4) fm has been obtained, which, together with the total number of participating nucleons being about 17, gives an estimate of $\rho = (1.8 \pm 0.5)\,\rho_0$ for the density of hot nuclear matter.

This value of density, combined with the "temperature" of nuclear matter T_0 = (190±10) MeV estimated from the slope of the secondary proton spectra within the interval of emission angles 70°-100°, gives a point on the nuclear matter phase diagrams shown in Fig. 18.

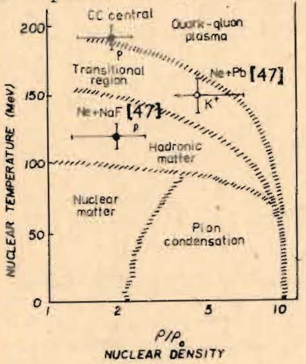

Fig. 18

As is seen from the figure, at moderate energies and for not very heavy nuclei, we can already be not far from a transition to the quark-gluon plasma. The result could be, however, more convincing if either heavier ions than carbon or much high energy are used.

At the end of my talk I would like to point out the following:

1. Relativistic nuclear physics is successfully being developed at Dubna. The program of experimental research in the field of relativistic nuclear physics being performed at JINR (primary synchrophasotron) directly connects important problems of high energy physics, which have been discussed at many Conferences of High Energy Physics.

2. The nuclear collisions in the region of limiting nuclear fragmentation are the unique source of extremely important information on a space-time picture of hadron production (and their internal structure) and also on the quark-gluon structure of nuclei. In particular, the regularities which follow from the experimental data on cumulative hadron production provide an evidence for the existence in nuclei of multiquark configurations the structure of which strongly differs from free nucleons. Quark-parton models assuming the existence of such a kind of states in nuclei seem to be able to explain the behaviour of nuclear formfactors, deep inelastic lepton scattering and particle production in the cumulative region. Substantial differences exist, however, between formulations of these models, and they should be reformulated in a consistent way.

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Кузнецов А.А. E1-85-175

Результаты Дубны в области предельной фрагментации ядер

В данном обзоре приводятся наиболее значимые результаты экспериментальных исследований в области предельной фрагментации ядер, выполненные разными группами физиков ОИЯИ в последнее время на Дубненском синхрофазотроне.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1985

Kuznetsov A.A. E1-85-175

Dubna Results in the Region of Limiting Nuclear Fragmentation

A review is given of the most significant results in the region of limiting nuclear fragmentation that have been obtained by different groups of physicists from JINR in the last few years at the Dubna synchrophasotron.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1985