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EXPERIMENTS AT THE DUBNA SYNCHROPHASOTRON

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In this report we present a brief review of the current state of the program of experimental research at the Dubna synchrophasotron in the field of relativistic nuclear physics. Some attention is being given to unique possibilities which we have at the High Energy Laboratory, JINR to carry out these studies and to the most significant physical results obtained recently by different groups of our physicists in the field of relativistic nuclear physics.

The relativistic nuclear physics is a new scientific field arising at JINR at the beginning of the seventies after that the acceleration of light nuclei to the highest energies had been performed at the synchrophasotron and the corresponding program of experimental research had been developed.

The implementation of new operating conditions at the synchrophasotron and the costructinn of a highly effective slow extraction system allowed us to obtain relativistic nuclear beams, the intensity of which is much larger than that of secondary particle beams.

The possibilities of the synchrophasotron extended after the successful acceleration of polarized deuterons in 1981.

The above possibilities of the synchrophasotron enable us to study systematically not only the behaviour of nuclear matter at small intermediate distances under extreme conditions but also completely new states of hadron matter (quark plasma), to check in detail the conclusions of chromodynamics in polarized experiments and to begin systematic studies of dynamic characteristics of interference in strong and weak interactions.

1. Present-day state of the synchrophasotron and its beams

As known, the beam of protons with an energy of 10 GeV was obtained at the Dubna synchrophasotron in 1957. During the ensuing three years the synchrophasotron was a record accelerator in the world. However, in connection with putting more powerful accelerators into operation at the beginning of the sixties, it lost its leading position. The way out of the situation was found: it was suggested to accelerate at the synchrophasotron nuclei heavier than hydrogen/1/ and also to develop and to carry out the corresponding program of experimental research/2/. These suggestions were successfully implemented at the beginning of the seventies on A.M.Baldin's initiative and with his direct participation/3/.

The fulfilment of new operating conditions of the synchrophasotron required to solve a series of complicated scientific-engineering problems. One of the main problems was to develop and to construct special-purpose sources of high charge ions.

Over a short period of time two types of new sources (laser/4/ and electron-beam/5/) were constructed at the High Energy Laboratory (HEL), by means of which the acceleration of light nuclei was carried out.

The source of ions, constructed using a solid-body laser, allowed beams of high charge ions of carbon and aluminium to be obtained with a high enough intensity. These ions were accelerated in the synchrophasotron and injector, respectively. Yet it proved inexpedient to use the laser type source at the synchrophasotron owing to its insufficiently large repetition of pulses and low efficiency. Since 1977 a regular operation of the more effective electron-beam ion source KRION-1 has begun at the injector of the synchrophasotron. This source made it possible to increase the intensity of previously accelerated nuclei and to accelerate heavier nuclei. The production of high charge-ions in the source KRION is achieved by means of a sequential process of neutral gas ionization by an electron beam formed in a superconducting solenoid.

As already mentioned, the acceleration of polarized deuterons was successfully accomplished at the synchrophasotron in 1981. This became possible due to the construction of a source of polarized deuterons (POLARIS)/6/ at the High Energy Laboratory. At present the intensity of a beam of polarized deuterons accelerated in the synchrophasotron is about $2\cdot10^{8}$ deuterons/pulse at the output from the main ring of the accelerator, and the degree of polarization is more than 40%.

Currently the set and intensity of nuclei (protons - 10 GeV, nuclei - 4.1 GeV/nucleon) accelerated at the synchrophasotron up to maximum energy are the following:

Type of nuclei	Intensity per pulse
p	$4\cdot10^{12}$
d	$4\cdot10^{12}$
$\uparrow$d	$6\cdot10^{8}$
He^{2+}	$5\cdot10^{10}$
C^{6+}	$4\cdot10^{6}$
O^{8+}	$4\cdot10^{5}$
Ne^{10+}	10^{3}

A beam of nuclei accelerated in the synchrophasotron can be ejected in one cycle of acceleration in two directions: I and II. In direction I beams of nuclei are extracted up to maximum energy with a duration of ~ 500 ms. In so doing, the efficiency of beam extraction in this direction is more than 90%. In direction II beams of nuclei are extracted to maximum energy with a duration of ≤ 1 ms or to average energy (several hundreds MeV/nucleon) with a duration of ~ 200 ms. In direction I a primary beam enters the experimental hall having an area of 6000 m^2, where it can be directed into one of eight channels (see fig. 1). In this case four experimental set-ups can operate simultaneously on beams of secondaries produced from the targets placed in the main direction. In direction II a beam is ejected into one of the two bubble chambers (2m propane or 1 m liquid hydrogen) or is used to perform studies at average energy (see fig. 2).

The total running time of the accelerator is 4000 hours a year. 85% of the total machine time are to implement the program of research in the field of relativistic nuclear physics and 15% to study operating conditions of the synchrophasotron and its beams. Breakdowns of the accelerator due to its faults do not exceed 7% of the planned time.

A further development of the synchrophasotron as an accelerator of relativistic and polarized nuclei will be continued in the current five years. It is assumed to put a new high-frequency accelerating system into operation, to improve the vacuum in the main ring of the accelerator due to cryogenic pumping, to enlarge the set of accelerated nuclei, to raise the intensity of beams of nuclei and secondary particles, to increase the number of beam channels and the coefficient of simultaneity of experiments carried out.

II. Program of experimental research at the Dubna synchrophasotron in the field of relativistic nuclear physics

At present studies in the field of relativistic nuclear physics and quark matter properties have acquired prime importance for the program of experimental research at the Dubna synchrophasotron. To perform these studies, more than 15 large experimental set-ups of different types from the Laboratory and other scientific-research centres of JINR member-countries are used. At the High Energy Laboratory there is the following set of detectors aimed at the above field of research. Five track (2m propane and 1m liquid hydrogen bubble chambers, spectrometers of the hybrid GIBS and RESONANCE

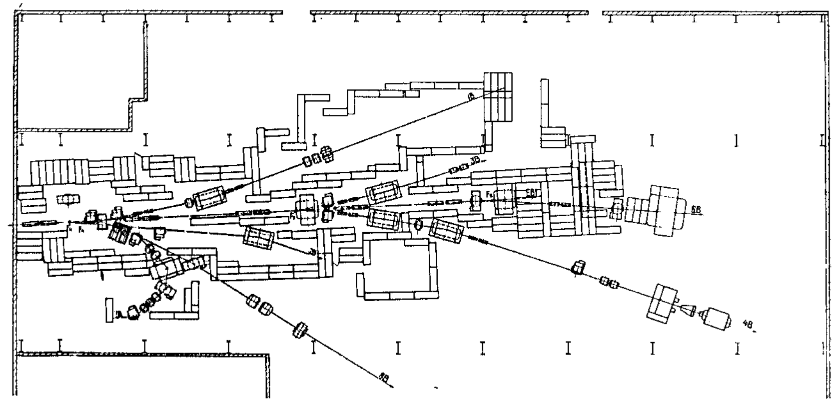


Fig. 1

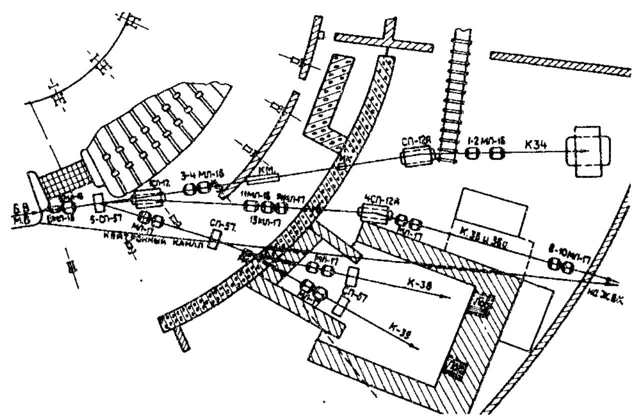


Fig. 2

type using streamer chambers, nuclear emulsions) and four electronic (spectrometers DISK, SYAO, ALPHA and PHOTON) set-ups operate on beams of the synchrophasotron. To solve the problems of relativistic nuclear physics, three large set-ups of the High Energy Laboratory (2m liquid hydrogen bubble chamber, spectrometers BIS-2 and TAU) are used in experiments carried out at the Serpukhov accelerator. Some aspects of relativistic nuclear physics are being studied by the JINR-CERN collaboration at the CERN accelerator in the NA-4 experiment.

Using the above set-ups, a great deal of information in the field of relativistic nuclear physics has been already obtained. A large number of physicists from JINR member-countries and other countries are concerned with the analysis of this information. As a result of the studies already performed, a series of experimental facts, unknown previously and important for a further development of theory, has been observed. These facts have been confirmed at other scientific centres and have been generally recognized /7/.

Experimental research in the following main fields has become traditional, to an extent, for the Dubna synchrophasotron::

- study of cumulative effect, processes of hadron production, and a space-time picture of hadron generation;
- study of hard collisions and polarized effects in processes with large momentum transfers;
- search for manifestations of a phase transition of hadron matter to quark plasma and relation to the problem of confinement and hidden colour;
- search for and study of exotic particles not described by conventional quark models;
- search for and study of hypernuclei, multiplets involving quark with charm etc.;
- study of dynamic properties of processes for which predictions are expected relating these properties to present-day formulations of field theory.

The above fields make up the program of experimental research at the Dubna synchrophasotron. As can be seen, experiments, the results of which are important for the construction of quantum chromodynamics of large distances, quark plasma theories, mechanism of quark confinement etc., are of particular significance in this program.

The urgency of these fields of research is obvious, and their practical implementation is directly related to the conditions of

carrying out experiments created at the Dubna synchrophasotron.

The prospects of scientific research at the Dubna synchrophasotron for the development of fundamental interaction theory and quark theory of nucleus can be illustrated, in our opinion, by physics results that have been already obtained at the accelerator by specialists of the Laboratory.

III. Review of physics results obtained recently at the Dubna synchrophasotron

Below we discuss some experimental results that have been recently obtained at the synchrophasotron by different groups of physicists from the High Energy Laboratory. Results of earlier studies can be found elsewhere /8/.

Experimental test of consequences of the hypothesis of cumulative effect and quark-parton structure functions of nuclei. We deal with results of a study of nuclear reactions with large momentum - energy transfers. The study of these processes has led to the discovery of cumulative effect and previously unknown universal regularities in the region of nuclear limiting fragmentation.

First the hypothesis of cumulative nuclear effect was advanced by A.M.Baldin in 1971 /9/. According to this hypothesis, in interactions of elementary particles with nuclei there occur particles in the kinematical region forbidden for interactions with nucleons of the nucleus at rest. In this case properties of cumulative particles should be determined not by geometric characteristics of colliding objects but by local features of hadron matter, i.e. they must satisfy the principles of local interaction and scale invariance.

The hypothesis of cumulative effect was experimentally confirmed already in first experiments carried out by V.S.Stavinsky's group /10/ at DISK in a beam of relativistic deuterons. In particular, such important properties of cumulative effect were found as scale invariance of inclusive spectra of pions produced by deuterons and anomalous (enhanced) A-dependence of inclusive production cross sections of pions in these processes. A year later the latter fact was confirmed in proton-nuclear experiments for large momentum transfers performed by J.Cronin /11/.

During the ensuing years the A-dependence of the inclusive cross sections for particle production in different type nuclear collisions has been studied in a number of experiments /12/. The obtained experimental data are commonly approximated by a dependence of the form A^{α}, and it is confirmed that α can be larger than 1. In fact, the enhanced A-dependence of the inclusive cross sections implies that the cross section should be proportional to the nucleus volume ($\sigma \sim A$).

In the experiments of V.S.Stavinsky's group it has been convincingly shown that the approximation of $\sigma \sim A^{\alpha}$, where $\alpha > 1$, is unfounded. It is good only in the case when the cross sections are measured for a small number ($\sim 3\div 4$) of nuclei (this takes place for most experiments under discussion). The group of V.S.Stavinsky has also measured the yields of particles with large momentum transfers for more than 20 nuclei and has shown that $\sigma \to A$ for all cases, i.e. $\alpha = 1$. The validity of this statement is convincingly illustrated by experimental results of the group of V.S.Stavinsky/13/ obtained for a broad range of A nuclei and different types of produced particles in pA and dA interactions. These results are presented in fig. 3 a,b. One can see that at first the cross sections for pions sharply increase with increasing A and then (from $A \approx 20$) remain, within the errors, approximately constant per one nucleon of fragmenting nucleus. The character of the A-dependence of the cross sections for kaons and protons is significantly different from the pion case: for these particles the production cross sections, normalized to A, increase as A increases and a transition to the $\sigma \sim A$ dependence appears to proceed only for $A \approx 100$.

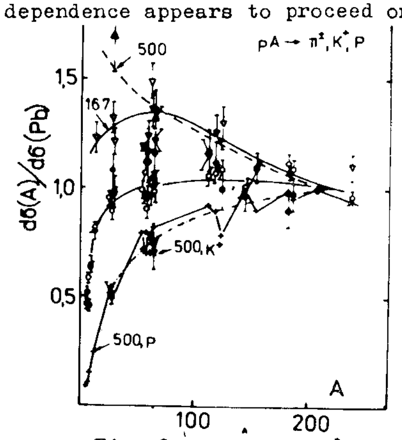


Fig. 3a

Designations:

- o – π^-
- ● – π^+
- ★ – K^+
- \+ – p

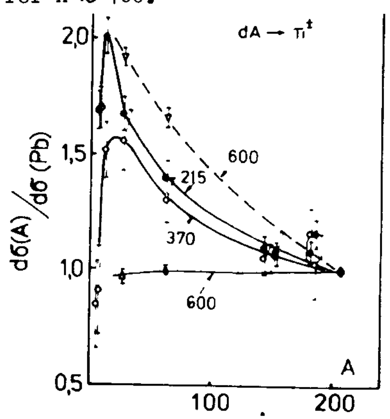


Fig. 3b

Designations:

- Δ – π (168°)
- ∇ – π (90°)
- o – π (180°)
- ● – π (180°)

As seen from fig. 3b, a similar character of the A-dependence of the inclusive cross sections of particle production is also observed for dA interactions.

A more detailed analysis of the experimental data has shown that the character of the A-dependence of the inclusive cross sections for fast particle production on nuclei into the backward hemisphere is determined not by the momentum of these particles and not by their emission angle but by the value of cumulative number A/14/. Here the variable X differs from the Bjorken variable x. The relation between them is found for reactions of the I + II → 1 +... type as follows/14/. Using the conservation law and the hypothesis of minimal missing mass, neglecting the relative motion of partons in objects I and II, one can write the expression

$$\left(P_I + X\frac{P_{II}}{A_{II}} - P_1\right)^2 = \left(M_I + X\frac{M_{II}}{A_{II}} + m_2\right)^2$$

where m_2 is equal to 0 for pions, m_k for K^--mesons and so on. From this it follows

$$\frac{X}{A_{II}} = \frac{(P_I\cdot P_1) + M_I m_2 + (m_2^2 - m_1^2)/2}{(P_I\cdot P_{II}) - M_I M_{II} - (P_{II}\cdot P_1) - M_{II} m_2}$$

In the case, e.g., of deep elastic scattering of leptons, neglecting their masses, we obtain the sought relation between the above-mentioned variables

$$\frac{X}{A_{II}} \approx \frac{-1/2\,(P_I - P_1)^2}{(P_I\cdot P_{II}) - (P_{II}\cdot P_1)} = -\frac{q^2}{2\,(P_{II}\cdot q)} = x$$

Figure 4 presents experimental data/13/ on the X-dependence of degree index n in $\sigma \sim A^n$, where $n = \frac{\ln f(A_{Pb})/f(A_{Al})}{\ln A_{Pb}/A_{Al}}$ for pA and dA interactions. One can see that n increases from 2/3 to 1 when X varies between 0.4 and 1, and for $X > 1$, within the errors, the value of n does not change and its values are grouped around 1. A similar character of the A-dependence of the inclusive cross sections is also observed in experiments of L.S.Schröeder et al./7/ in pA collisions at 0.8-4.89 GeV and in pion-nucleus and gamma-nucleus interactions/15,16/.

Consequently, the behaviour of the enhanced A-dependence of the inclusive cross sections found in the studies of cumulative effect is universal in character and represents a characteristic property of particle production processes in nuclear collisions with large momentum transfers. In this connection the conclusions of

Fig. 4

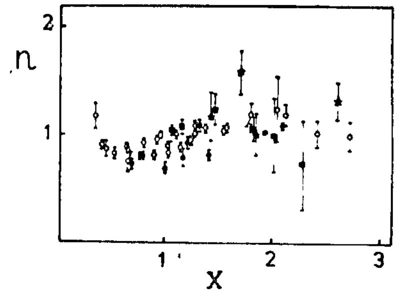
pA and pd-interactions:

● π(pA)

o π(pd)

■ K^- } (pA)

★ K^+



A-dependence such as $\sigma \sim A^n$, where $n > 1$, are insufficiently valid because they are based on experiments carried out with a very small number of nuclei/12/. The analysis of experimental data performed by A.Melissinos/12/ confirms this point of view.

During the ensuing years the processes of cumulative particle production have been studied experimentally and theoretically/17/. A series of experimental research, performed in nuclear interactions of different types and over a broad range of energies, has allowed one to ascertain the universal character of main properties of cumulative effect: scale invariance, the dependence of particle production cross sections on cumulative number, an extremely weak dependence of cross sections on quantum numbers of cumulative particles etc.

It is difficult to interpret theoretically these and other experimental regularities without using quantum chromodynamics and quark-parton models. In fact, as already mentioned, the notion of cumulative effect has originated from the idea of local hadron interaction at large momentum transfers and from the fact that a point-like object perceiving a momentum larger than that of the whole nucleon belongs to the group of nucleons of the nucleus/9/. This means that, in studying cumulative processes, specific multiquark interactions are investigated which are directly related to the collectivization of quarks of the nucleus, i.e. quark-parton structure functions of nuclei are irredicable to one-nucleon. In this connection, to describe the properties of cumulative processes, it is more natural to use the quark-parton model of hard collisions which comprises the ideas of the point-like character of hadron interactions, a relatively weak coupling of quarks inside hadrons and is an analog of impulse approximation in nuclear physics.

Using these fundamental properties, the quark-parton model allows the cross section of hard collisions of hadrons to be expressed as the product of the elementary interaction cross section of quarks b, containing in hadron B, and the momentum distribution function of quarks b in hadron, $G(x, Q^2)$. The function

$G(X, Q^2)$ is the quark-parton structure function of hadron B, x is the fraction of longitudinal momentum P of hadron B which is carried by quark b and Q^2 is the four-momentum squared transferred in the collision. Thus, the cross section of the hard collision process of hadrons represents the sum of the cross sections of noncoherent scattering on all quarks which are present, to some probability, in hadron B.

In the case, e.g., of deep inelastic scattering of leptons on hadrons $\sigma_0 = A_b/Q^4$, $x = Q^2/2(P\,q)$ and $Q^2 = -q^2$.

As hadrons and nuclei are equally complex objects, quark-parton structure functions of nuclei can be introduced by analogy to hadrons. In this case the distribution of quarks in the nucleus is defined by the function $G(x, Q^2)$, and a momentum per one nucleon is introduced instead of that of the whole nucleus (P), i.e. $P_0 = P/A$ and $X_0 = XA = Q^2/2\,(P_0 q)$.

For cumulative processes $X_0 \geqslant 1$. This means that the probability that the constituent (quark) carries the momentum of a group of nucleons is determined by the function $G(X_0, Q^2)$ in this range of X_0 values. Thus, quark-parton structure functions $G(X, Q^2)$ are not one-nucleon functions for nuclear collisions with large momentum transfers. They are independent characteristics of relativistic nuclear collisions.

More complete information on characteristics of quark-parton structure functions of nuclei has been obtained in experiments on an investigation of nuclear limiting fragmentation/13/ performed at the synchrophasotron using the study of the properties of inclusive processes in the cumulative region. In the region of nuclear limiting fragmentation, which, as found/18/, begins from an energy of 3.5 GeV/nucleon, the cross section of inclusive process A+B → C+... (normalized to the atomic weight of the nucleus) in the cumulative region is proportional to the quark-parton structure function of nuclei/19/

$$\frac{E\,d\sigma}{A\,dP} \approx G(X, P_\perp^2)$$

An explicit form of the $P_\perp^2$ -dependence of function $\phi\,(P_\perp^2)$ has been found experimentally/13/. This dependence, measured in reactions of different types and for a variety of energies, is well described by a unique expression

$$\phi\,(P_\perp^2) = \frac{f(X, P_\perp^2)}{f(X, 0)} = 0.9\,\exp\,(-2.7\,P_\perp^2) + 0.1\,.$$

If the cross section measured experimentally is normalized to the

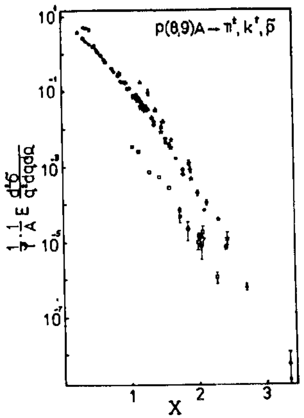


Fig. 5a

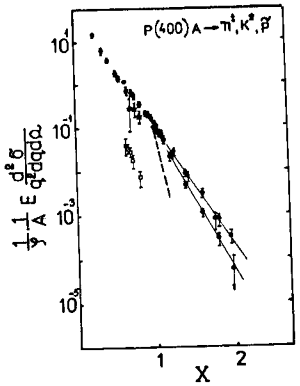


Fig. 5b

Designations:

- $\bullet$ - π^+
- $\star$ - K^+
- $\square$ - K^-
- $\blacklozenge$ - $\bar{p}$

function $\phi(P_\perp^2)$, one can obtain the function $G(X, P_\perp^2)$ depending only on X, i.e. $G(X, 0)$.

The validity of this statement has been tested experimentally by the group of V.S.Stavinsky and later on in experiments at the Fermilab accelerator for large values of energy /20,21/. Results of the experiments are presented in fig. 5. From the figures one can draw the following conclusions: a) inclusive production cross sections of cumulative pions, kaons and other particles are described by a unique exponential dependence on X in proton interactions with a large set of nuclei and over an energy range from 8.9 to 400 GeV

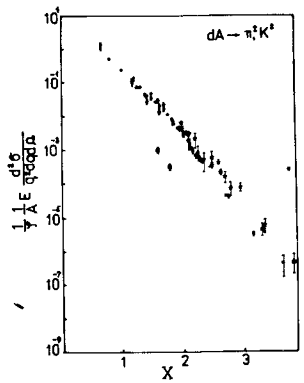


Fig. 5c

Designations:

- $\bullet$ - π^+
- $\star$ - K^+
- $\blacksquare$ - K^-

although the G(x) functions for K^- and $\bar{p}$ markedly differ from those for π and K^+-mesons in absolute value; b) parametrization of this dependence by expression $G(X) \sim \exp\left[-\frac{X}{\langle X \rangle}\right]$ leads to a universal value of $\langle X \rangle$ equal to ~ 0.14.

These results are extremely important for understanding the nature of cumulative effect. They directly point to the quark mechanism of cumulative processes. Indeed, the behaviour of the inclusive cross sections for cumulative charged pion and kaon production (namely, the equality of the cross sections for K^+ and $\pi^\pm$ and a strong difference of the cross sections for K^- and K^+) observed by the group of V.S.Stavinsky can be interpreted as a result of pickup from the symmetric quark sea of corresponding antiquarks by valence quarks of colliding objects. Then, e.g., the equality of the cross sections for K^+ and π^+ in the indicated process should be a result of pickup from the sea of $\bar{d}$ and $\bar{s}$ quarks by knocked out valence u quarks. The production of K^- in this way will be strongly suppressed.

The above properties, found in the study of cumulative nuclear processes in the region of limiting fragmentation, have allowed A.M.Baldin to make concrete predictions concerning the absolute value and X-dependence of deep inelastic scattering cross sections for muons on nuclei /19/. An experimental test of these predictions is of importance since the measurement of deep inelastic scattering cross sections of leptons on nuclei enables one to obtain, in a direct way, main data on the most important characteristics of quark-parton structure functions of nuclei.

The prediction of A.M.Baldin was experimentally tested in a joint JINR-CERN experiment at the CERN accelerator /22/. The group of NA-4 studied the inelastic scattering of negative muons on carbon nuclei for an energy of 280 GeV and a momentum transferred of $Q = 100$ GeV/c^2. The X-dependence of the quark-parton structure function of carbon nuclei was measured in the region $X \geqslant 1$. As predicted, the quark-parton structure function of nuclei had an exponential X-dependence, and the parameter X was equal to 0.14 ± 0.01. This result completely confirmed the conclusions, drawn previously in the measurement of the cross sections for cumulative particle production in collisions of relativistic nuclei, and the validity of interpretation of cumulative effect and its properties using QCD and quark-parton models (see fig. 6).

New interesting data on cumulative processes have been recently obtained in the group of V.B.Lyubimov /23/ in the analysis of

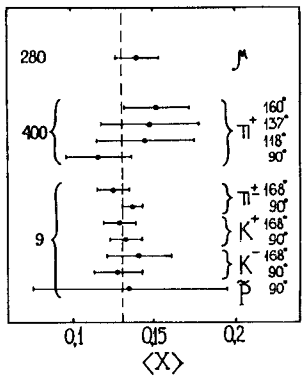


Fig. 6

pictures from the 2m propane bubble chamber exposed to negative 40 GeV/c pions at the Serpukhov accelerator. For the first time cumulative processes were studied in experiments different from inclusive ones, i.e. in this case the technique allowed the charactetistics of "accompanying" particles to be investigated along with cumulative particles. Such experimental conditions made it possible to obtain more abundant information on the dynamics of cumulative processes. In particular, the experiment allowed one to determine more valid selection criteria of cumulative reactions, to measure their cross sections, to obtain important information on the characteristics of multiple hadron production, to find correlation effects between "meson" and "nucleon" cumulative interactions.

The experimental material involved about 19000 inelastic $\pi^- C$ interactions. In the analysis the characteristics of secondary charged particles were studied in detail versus the variable β_c which defines the degree of cumulativity of pions or protons. With this aim the cumulative number of pions/protons was chosen in each event, i.e.

$$\beta_c = \max\{\beta_i\}$$

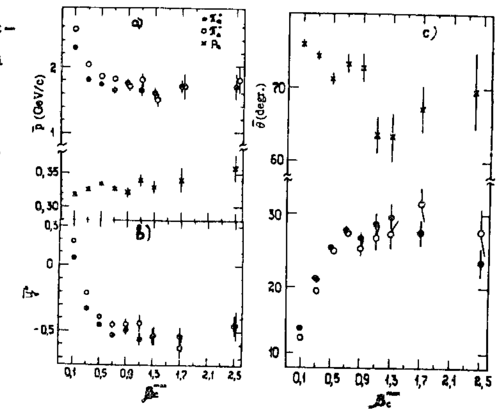
where

$$\beta_i = \frac{E_i - P_{iz}}{m}$$

determines the order of particle cumulativity or, in other words, the minimum target mass which is required for the production of hadron with energy E_i and momentum projection on the reaction axis p_{iz}.

The summary experimental data on all the studied characteristics of pions and protons (average multiplicity, average momentum and angle in the laboratory system, average rapidities etc.) allowed two groups of events to be separated, for which the behaviour of the above properties is distinctly different versus β_c: group I is characterized by $\beta_c \leq 0.6$ for pions and $\beta_c \leq 1.2$ for protons, and group II has $\beta_c > 0.6$ for pions and $\beta_c > 1.2$ for protons. This fact is illustrated in fig. 7(a,b). In particular, in fig. 7 one can see that a) the following dependence on β_c is inherent in the pions

from group I: the average multiplicity and average emission angle of accompanying mesons increase with increasing β_c, and their average rapidities shift to the region of nucleus-target fragmentation. For the pions from group II all the indicated average characteristics do not change with changing β_c; b) for the protons from group I one can observe a sharp increase of average multiplicities and average emission angles with increasing β_c and a decrease of average momentum. For the protons from group II all the indicated



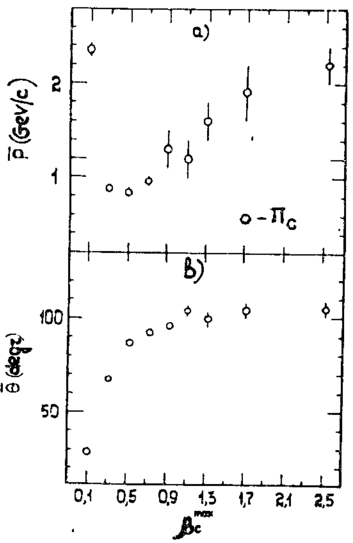


Fig. 7a

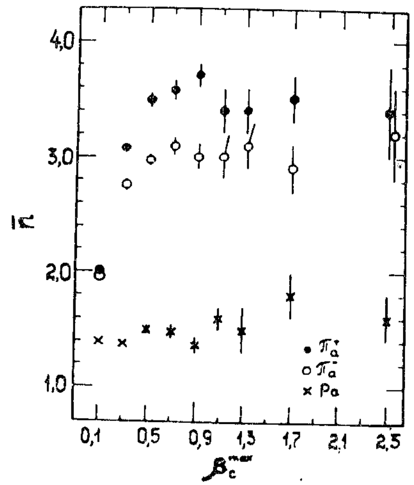


Fig. 7b

average characteristics do not change with changing β_c. Such a character of the observed correlations of the properties of secondary charged particles versus β_c points to the existence of two independent sources of pion and proton production, one of which creates the group of events with $\beta_c > 0.6$ for pions and $\beta_c > 1.2$ for protons (group II) and has the general nature-cumulative pion and proton production. The analysis of the events from group II has shown that the processes, which lead 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 the degree of cumulativity of protons. The estimate of the cross sections for the processes of cumulative pion and proton production gives the same value equal to ~ 11 mb. This fact eliminates the statement of their large (~ 100 times) difference, and this is probably due to a more correct choice of the selection criteria of cumulative groups of these particles.

The experimental conditions also made it possible to measure the invariant inclusive production cross sections of pions and protons emitted into the backward hemisphere in the laboratory system. For the pions from group II ($\beta_c > 0.6$) the cross section is well factorized by the dependence

$$E\frac{d^3\sigma}{dp^3} \approx \exp(-P_\perp^2/\langle P_\perp^2\rangle)\exp(-\beta_c/\langle\beta_c\rangle)$$

In so doing, when fitting the experimental data, the best values of the parameters have been obtained: $\langle P_\perp^2\rangle = 0.18 \pm 0.02\ (\mathrm{GeV}/c)^{-2}$ and $\langle\beta_c\rangle = 0.14 \pm 0.004$. It should be noted that the value of $\langle\beta_c\rangle$ is in good agreement with the one of universal constant $\langle X\rangle$ obtained previously in experiments on nuclear limiting fragmentation and in lepton-nucleus collisions with large momentum transfers.

The behaviour of the inclusive cross sections for the pions from group II versus the multiplicity of pions emitted into the backward hemisphere does not vary with increasing the multiplicity of these pions. It has been found that for $n_\pi \geqslant 2$ the value of $\langle\beta_c\rangle$ does not differ, within the errors ($\langle\beta_c\rangle = 0.130 \pm 0.005$), from the value of $\langle\beta_c\rangle$ obtained for events with $n_\pi = 1$. This fact agrees with the hypothesis of soft quark hadronization and serves as an additional argument in favour of using quark-parton structure functions of nuclei as main characteristics of relativistic nuclear collisions.

The invariant inclusive production cross sections of protons, emitted into the backward hemisphere in the laboratory system, versus β_c have an exponential behaviour only for the protons from group II. In this case the value of $\langle\beta_c\rangle$ is somewhat larger than for pions, and it increases with increasing the multiplicity of protons.

The properties of all secondary particles accessible for measurement and identification were studied in the discussed

experiment. In addition to the properties of the discussed types of pions and protons, the characteristic features of the behaviour of leading pions were also investigated versus β_c. The average characteristics of leading pions were found to be independent of cumulative number (see fig. 8) β_c. This points to the fact that leading pions are produced due to spectator quarks which pass through the nucleus without interaction, and cumulative particles are produced as a result of hard collisions of another quark of the incident pion.

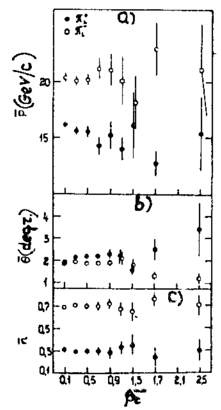


Fig. 8

<u>Multiple production processes of fragments and particles in relativistic nuclear collisions</u>. The processes of "direct" emission of nucleus fragments and multiple particle production form a main part of the total cross section of relativistic nuclear interactions. The summary results obtained at the Dubna synchrophasotron allows a complete enough picture of characteristic properties of these processes to be formed. In particular, it has been found that the main characteristics of multiple production processes are well described by superposition of the characteristics of nucleon-nucleon interactions and that in multiple processes the average transverse momentum of particles is limited, independent of the energy of colliding objects and equals ~ 350 GeV/c. These and other experimental facts enable multiple production processes to be described theoretically by means of the models, in which nucleons are good quasi-particles. At present the best model is the additive nucleon model. A comparison of the experimental data and the calculations by this model shows a good agreement between them in all main characteristics of multiple production processes /24/.

Below we present a brief review of the experimental data, obtained recently at the Dubna synchrophasotron, on a study of multiple production processes of fragments and particles in relativistic nuclear interactions. Earlier results can be found in reviews /25/.

<u>Inelastic cross sections of nuclear interactions</u>. Presently a large number of papers /26/ is devoted to the measurement of inelastic cross sections of nuclear collisions for energies above 1 GeV/nucleon. The summary data are presented in fig. 9. In the same figure are given new results /27/ on the measurement of inelastic cross sections

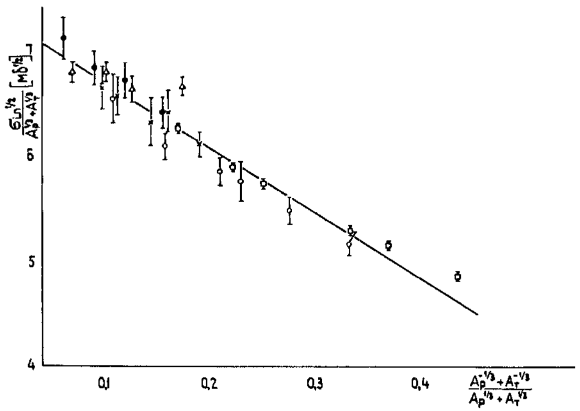


Fig. 9

for interactions of ^{22}Ne with C, Al, Cu and Pb nuclei at 4.1 GeV/nucleon. Available experimental data allow the following characteristic properties of inelastic cross sections for nucleus-nucleus collisions to be found: a) the cross sections, within the experimental errors, are independent of the energy of projectiles; b) there is a weak dependence of the cross sections on the size of target-nucleus (A_t) as the atomic weight of projectile (A_i) increases; c) the behaviour of the cross sections versus A_i and A_t is well described by a simple geometric model of interacting nuclei with overlap, in which the parameter of overlap depends on the atomic weights of colliding nuclei. A comparison of the experimental data and the calculations by this model gives the value of overlap parameter equal to $\beta \approx 0.93$

Multiple production processes of fragments. Not all nucleons of the incident nucleus interact in the inelastic collision of relativistic nuclei with target-nucleus. Owing to a relatively weak coupling of nucleons inside the nucleus, a part of them after the interaction remains spectators (stripping nucleons). Not only nucleons but also projectile fragments (fragments of the nucleus) can be stripping objects in collisions of nuclei heavier than deuteron.

Figure 10(a) presents the summary data on the probability of stripping fragment (^2H, ^3H and ^3He) production in interactions of α-particles with a momentum of 4.5 GeV/c/nucleon versus the atomic weight of target-nucleus, and figure 10(b) shows the cross sections of the yields of isotopes ^1H, ^4He, ^6Pi, ^9Be, ^{10}B, ^{12}C produced in the collision of carbon nucleus with tantalum at 4.2 GeV/c per nucleon. These results have been obtained at the synchrophasotron by means of the 2m propane bubble/29/ and streamer/30/ chambers, HEL. As seen, the probabilities of stripping fragment production turn out to be rather large, and the fragmentation cross section can be presented, within the errors, as the dependence $\sigma_f \sim A_t^n$ with $n \approx 0.3$

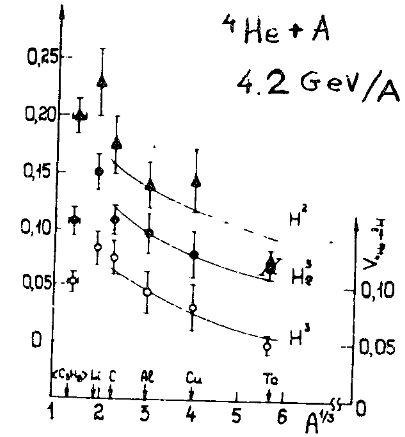


Fig. 10a

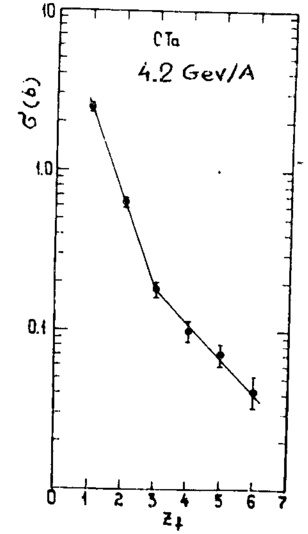


Fig. 10b

for all fragmenting channels. However, in the case of selection of a group of events with small impact parameter (the so-called "central" interactions), the fragmentation cross section has a stronger dependence on A_t: for this group of events the parameter n becomes equal to 1.01 ± 0.06.

The enhanced A-dependence of the cross sections for nuclear fragment productinn was observed in the experiment on a study of fragment production processes in pA interactions with different transverse momenta/31/. As the transverse momentum of the fragment produced increases, the value of parameter n rises from 2/3 to unityand becomes $\geqslant 1$ at $P_\perp > 1$ GeV/c. This dependence is shown in fig. 11.

Remind that at first for $n = 1$ the enhanced A-dependence was observed in experiments on cumulative particle production. The data on fragmentation presented above confirm the conclusion of universality of this effect.

Interaction cross section of charged stripping fragments. In a number of papers/32/ it has been reported on the observation of the effect of increasing the interaction cross section of stripping fragments with charge $\geqslant 2$ of projectiles.

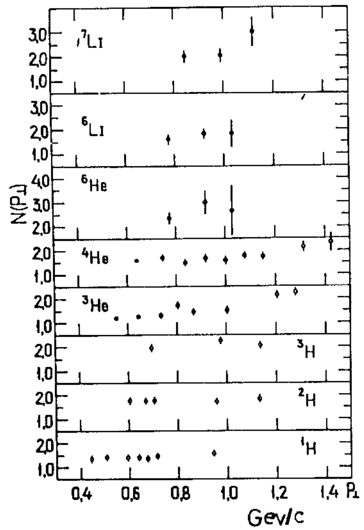


Fig. 11

Recently this effect has been studied by the group of the 2m propane bubble chamber, HEL in conditions when carbon with an energy of 4.2 GeV/nucleon is an incident nucleus[33]. Interaction cross sections for carbon projectile fragments with Z = 5 and 6 in propane were measured (see fig. 12a) versus the distance from the primary vertex. The charge of the fragments was identified by the density of δ -electrons and by evaluating the total charge of stripping fragments of primary and secondary stars. Interaction cross section for the projectile carbon fragments with charge 5 and 6 in propane was found to be bv ~ 10% larger than the expected value (see fig. 12b). This result indicates a possible existence of excited fragments with an anomalously large cross section and an excited state lifetime of $\leqslant 10^{-10}$ s.

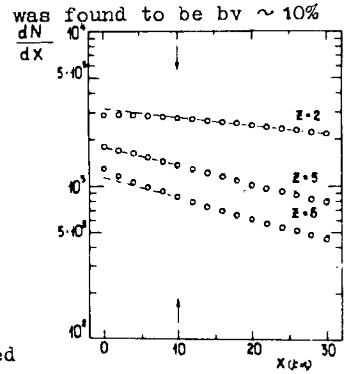


Fig. 12a

<u>Total disintegration of heavy nuclei</u>. The study of this interesting physics phenomenon was begun at the High Energy Laboratory in papers[34]. The total disintegration of emulsion heavy nuclei was found to occur, to a pronounced probability, under the effect of ~ 10 GeV protons. A similar effect was observed in experiments at the Serpukhov accelerator in an exposure of nuclear photoemulsions to ~70 GeV protons[35]. The acceleration of nuclei at the Dubna synchrophasotron allowed these studies to be continued for relativistic nuclear collisions. Below we report on new experimental results on the total disintegration of heavy nuclei obtained by the group of K.D.Tolstov[36].

Most part of the investigations was carried out using BR-2 nuclear emulsions (GOSNIIKHIMFOTOPROEKT), emulsions enriched with different types of nuclei and lead salts. Both methods of emulsion

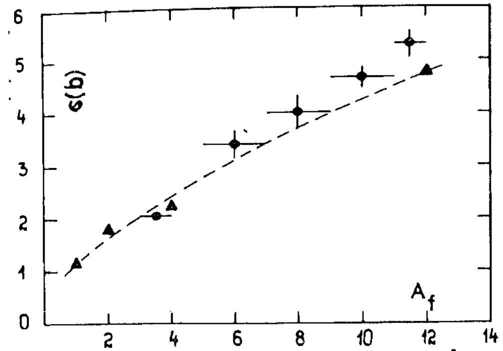


Fig. 12b

enrichment were developed at the High Energy Laboratory.

The events, in which the sum of g- and b-particles $N_g+N_b=N_h \geqslant 28$, were considered as the events of total disintegration of Ag and Br nuclei. The total charge of the indicated particles for this group of events was found to be 41, i.e. it coincided with the average charge of Ag and Br. The events of total disintegration of Pb nuclei were selected providing $N_h \geqslant 40$. Here g and b are particles having energies of $20 < T_p < 400$ MeV and $T_p \leqslant 26$ MeV for protons, respectively.

In the experiment it has been found that for the events selected in this way there takes place mainly the emission of individual nucleons and there is no residual nucleus.

The data on the probability of total disintegration of nuclei, average multiplicities of s-, g- and b-particles, average energies of g- and b-particles are presented below in the table.

As seen from the table, the probability of the process of total disintegration of nuclei depends only on the atomic weights of colliding nuclei and is independent of the energy per nucleon of projectile. The average nultiplicities of g- and b-particles and their redistribution are practically invariable with increasing energy, whereas the value of $\langle n_s \rangle$ increases by a factor of ~ 4. Consequently, the total disintegration of nuclei is not due to ions production and (or) their subsequent interactions inside the nucleus (i.e. cascade processes). A stronger energy spectrum of protons

Table

Energy in GeV	10	70	70	14	14	43
Type of interaction	P+Ag,Br		p + Pb	^{4}He+Ag	^{4}He+Pb	^{12}C+Ag
W	3.1±0.6	3.0±0.7	7±2	6.4±1	10±2	17±2
$\langle n_s \rangle$	4.0±0.5	17.1±0.8	20.7±1	7.4±0.4	12.5±1	18.6±0.7
$\langle n_g \rangle$	10.0±0.8	14.2±0.8	23±1	18,0±0.7	34.7±2	22.3±0.8
$\langle n_b \rangle$	22.0±1.2	15.8±0.1	19.8±0.4	15±1	12.7±1.3	11.1±0.5
$\langle T_g \rangle$	120 ±12	-	-	138±4	-	148 ± 3
$\langle T_b \rangle$MeV	19 ± 2	19.2±1	18 ±2	18 ± 2	22 ± 2	17 ± 1

($26 < T_p < 400$ MeV), when passing from average interactions to events of total disintegration of nuclei, is not described by the cascade-vapour model (CVM) since the value of $\langle T_p \rangle$ = 123 MeV calculated by the CVM proves to be smaller than the experimental one: $\langle T_p \rangle$ = 138± ± 3 MeV for the events of total disintegration of Br and Ag nuclei produced by ^{4}He. All the above facts show that at total disintegration of nuclei there is a possible manifestation of collective effects such as, e.g., hydrodynamic type interaction. In fact, if the shock wave model is used, one cannot expect (as discussed previously) a strong angular collimation of such light fragments as nucleons and α -particles due to flattening the angular distribution which follows from the transverse momentum component of nucleons of the nucleus. For fragments with large charge this influence should be much smaller. The fact that there exists the emission direction of fragments with charge $\geqslant 4$, produced in the interactions of C with emulsion heavy nuclei, is shown in fig. 13.

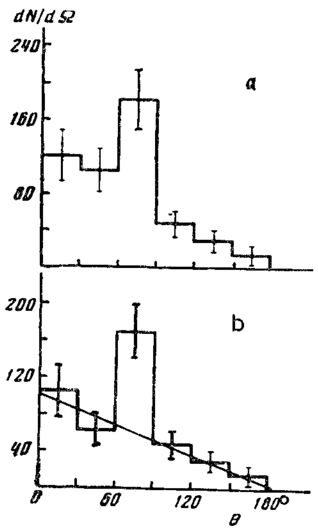


Fig. 13

Multiplicity of secondary particles in nuclear interactions. As known, the summary data obtained in hadron-nucleon and hadron-nucleus interactions at high energy demonstrate the existence of a weak dependence of $\langle n \rangle / D$ on the energy and atomic weight of projectile/37/. If the charge of an initial system is taken into account in the analysis of the multiplicity distributions of secondary particles, all available data for the interactions indicated can be described by a universal dependence of the type $D = a\langle n \rangle + b$. New experimental data on the multiplicity of secondaries produced in nucleus-nucleus interactions have destroyed this universality. The results obtained at the Dubna synchrophasotron by means of track devices show that the behaviour of the multiplicity distributions for charged pions in nucleus-nucleus interactions is noticably distinct from the above dependence for heavy (from C) nuclei: the value of D increases much faster with rising $\langle n \rangle$. This effect is shown in fig.14. The dependence of D on $\langle n \rangle$ observed in nucleus-nucleus interactions can be explained within the framework of the model of independent interaction of projectile nucleons/38/. The assumption that in nucleus-nucleus (A_i+A_t) collisions the projectile nucleons interact with target-nucleus independently is at the root of this model.

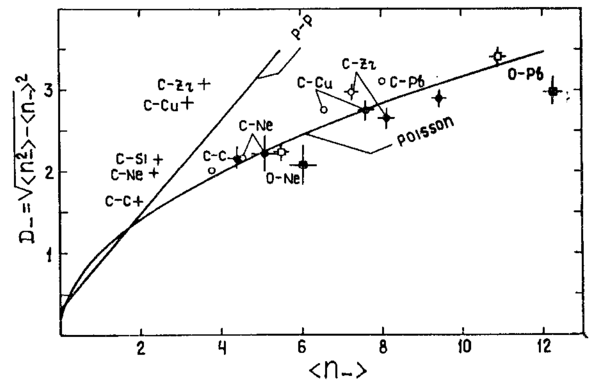


Fig. 14. The dispersion $D = \sqrt{\langle n^2 \rangle - \langle n \rangle^2}$ versus $\langle n \rangle$ for $P(n_-)$ in inelastic ^{12}C + A interactions (+) and in central ^{12}C+A(o) and ^{16}O + +A(□) collisions at a veto angle of $\theta_{ch} = 2°$ for charged projectile fragment emission. ● - ^{12}C+A at θ_{ch}=4°. ■ - ^{16}O+A at θ_{ch}= 4°. The curve $D = \sqrt{\langle n \rangle}$ corresponds to the Poisson distribution and the line to the $P(n_-)$ distributions in pp interactions.

From here one can get the following expressions for average multiplicity $\langle n \rangle_{A_iA_t}$ and dispersion $D_{A_iA_t}$ through the corresponding characteristics of nucleon-nucleus ($N+A_t$) interactions:

$$\langle n \rangle_{A_iA_t} = \langle \nu_i \rangle \langle n \rangle_{NA_t}$$

$$D^2_{A_iA_t} = \langle \nu_i \rangle D^2_{NA_t} + \langle n^2 \rangle_{NA_t} D^2_\nu$$

where $\langle \nu_i \rangle = A_i \sigma_{NA_t} / \sigma_{A_iA_t}$ is the average number of projectile nucleons which interact with target-nucleus; D_ν is the ν_i -distribution dispersion (ν_i = 1, 2,..., A_i); σ_{NA_t} and $\sigma_{A_iA_t}$ are the inelastic cross sections of nucleon-nucleus and nucleus-nucleus interactions. A comparison of the experimental data and the calculations made by the discussed model shows a good agreement between them/39/.

When the events with small impact parameter ("central" interactions) were selected out of all inelastic nucleus-nucleus events, an essential narrowing (contraction) of the multiplicity distribution of pions was observed for them, i.e. the dependence of D on $\langle n \rangle$ agrees better with the Poisson distribution. It has been found/40/ that with changing a veto angle of stripping particle emission from 0° to 4° a relative width of the distributions $\eta = (\langle n^2 \rangle - \langle n \rangle^2)/\langle n \rangle$ significantly decreases remaining practically constant as the veto angle increases to 14°.

The observed behaviour of the multiplicity distributions of particles produced in nucleus-nucleus collisions does not confirm thermodynamic model predictions/41/.

Determination of dimensions of radiation region of secondary particles. Despite a large amount of data on the processes of multiple particle production, the question on the space-time structure of radiation sources of secondary particles remains urgent. To clarify this question, the method of interference of like particles produced in different type processes is widely used/42/. The possibility of applying this method to the determination of the radius of the radiation region (r) for secondaries and the lifetime of this system (τ) has been proposed and developed in papers/43/. Concrete information on the space-time structure of generation sources of secondaries in different processes has been obtained to date using this method/44/. In particular, at first the group of the 2m propane bubble chamber has found that for pions produced in π^-p interactions at 40 GeV/c, the size of the radiation region is characterized by $r \approx (1.9 \pm 0.3)$ fm and $\tau \approx (0.8 \pm 0.2)$ fm. However, later on the analysis of space-time characteristics of the same process in the c.m.s. allowed a more composite structure to be observed: the existence of two radiation sources of secondary pions, one of which is due to direct pion production ($r_1 \approx c\tau_1 \approx$ 1 fm) and another - to pion interference from the decay of resonances ($r_2 \approx c\tau_2 \approx$ 3 fm).

Recently this group has made an attempt to determine the dimensions of the radiation region of secondary pions in the c.m.s. of quarks belonging to interacting particles/45/. Experimental data have been obtained in the analysis of events from π^-p, π^-n and π^-C at a momentum of 40 GeV/c.

To determine the size of the radiation region of like pions I and II, the experimental distributions of like pion pairs were approximated by an expression of the type

$$R(q^2) \approx a\left\{1 + \lambda\left[4J_1^2(q_\perp r)/(q_\perp r)^2\right]\right\}$$

where $\bar{q}_\perp = \bar{q} - (\bar{q}\bar{n})$, $\bar{q} = \bar{p}_1 - \bar{p}_2$, $\bar{n} = \bar{p}/|\bar{p}|$, $J_1(q_\perp \cdot r)$ is the first-order Bessel function, a-the normalized coefficient and λ- the parameter taking into account the influence of a number of experimental factors and possible specific correlations/46/. The indicated approximation was made in various reference frames determined by the ratio of the momenta of colliding particles $R = p_t/p_i$. When R = 0, this corresponds to the laboratory system (i.e. the nucleon is at rest); when R = 1, to the c.m.s. of pion and nucleon; when R = 1.5, to the c.m.s. of quarks/47/; when $R \to \infty$, to the antilaboratory system (i.e. the pion is at rest).

Using this procedure of experimental data analysis for π^-p and π^-n, the following has been found: the radius of the radiation region r varies versus R, and in all cases ($q_0^* = E_I - E_{II} \leq 300$ MeV) or q_0 is unlimited) its minimum is achieved at 1.5 which corresponds to the quark reference frame. In this case the parameter does not vary significantly with changing R, but it decreases with increasing q_0^* (see fig.15).

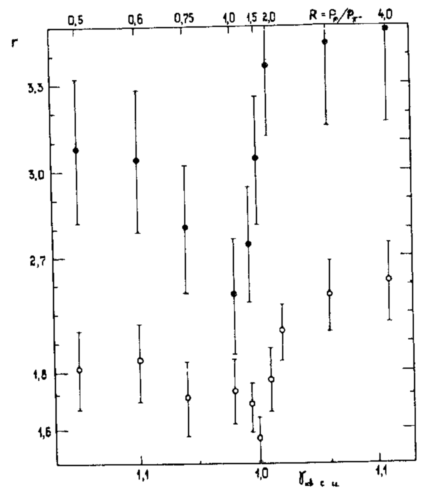


Fig. 15
Designations:
o - π^-N
• - π^-C

The "transverse" ($r_\perp$) and "longitudinal" ($r_\parallel$) sizes of the radiation region for pions versus R have been obtained for the same group of events. For the pairs of pions flying in the cone at $|\theta_{\pi\pi}| \leq 30°$ ($r_\perp$) and in an angular interval of $120° \leq \theta_{\pi\pi} \leq 60°$ ($r_\parallel$) relative to the collisions axis of primary particles it has been found that $r_\perp$ is always larger than $r_\parallel$ and invariable with changing R (true, if $R \approx 1.5$, there is a tendency toward decreasing $r_\parallel$, but this confirmation cannot be made due to large errors).

The analysis of the pairs of like pions produced in $\pi^- C$ has shown that the values of r versus R have a minimum at $R \approx 1$ which corresponds to the c.m.s. of pion and nucleon. This fact can be explained by a considerable contribution of multiquark interactions in the case of hadron-nucleus collisions at high energy.

Search for and study of exotic particles not described by conventional quark models. The question on the existence of particles not described by conventional quark models is to date one of the important problems of quark physics since this problem is directly associated with the existence of multiquark states/48/. The study of multiquark states, when quarks, belonging to the group of nucleons, are mixed, can give valuable information on the nature of asymptotic freedom and quark confinement.

To a large probability, the observation of multiquark states should be expected in processes with the participation of nuclei.

At the High Energy Laboratory the search for multiquark resonance states was first performed by the group of B.A.Shahbazian/49/ in the processing and analysis of pictures obtained by means of a 24-litre propane bubble chamber irradiated with 4 GeV/c π^--mesons and $\sim$ 7 GeV/c neutrons. The resonance states with hypercharge from 0 to 6 were searched for in the experiment. For this purpose the invariant mass spectra of systems, including Λ°-hyperons and different types of charged accompanying particles, were investigated. A detailed analysis of the invariant mass spectra of (Λp)-system allowed the existence of three excited states of Λp-dibaryons to be observed (to a high degree of confidence). The masses and widths of these resonances are given in Table I. The values of the corresponding quantities predicted by the bag model are also presented in the table/50/. One can see that the values predicted by this model agree surprisingly well with the experimental data. The resonance states observed can be interpreted as six-quark systems included in one bag.

As known, multiquark states are theoretically predicted at other values of masses as well. Further studies of the invariant mass spectra of the systems including Λ°-hyperons carried out by the group of B.A.Shahbazian have shown that some of the resonance states predicted by theory are in fact observed in the experiment/51/. The total results of these studies are presented in Table I.

Presently the search for and study of resonance states of the indicated type are being performed using the material obtained by

means of the 2m propane bubble chamber, HEL on beams of relativistic nuclei. Recently the same group has obtained the Λp-invariant mass spectrum, due to ^{12}C-propane interactions, using photographs of the 2m propane bubble chamber, exposed to a p = 4.2 GeV/c momentum relativistic ^{12}C ion beam.

Table I

I. Strange dibaryons-candidates for q^6-states

1. Λp (I = 1/2, Y = 1, B = 2, S = -1)

M (MeV/c^2)	Γ (MeV/c^2)	Significance ($N_{st.dev.}$)	$\sigma_{prod.}$ (μb)	Bag model predictions M (MeV/c^2)	Bag model predictions J^P
2255.2±0.4	16.9±2.3	8.05±1.32	85.3±20.0	2241	2^+
2354.3±0.7	56.1±5.0	6.25±1.25	65.0±17.0	2353	2^-
2183.2±0.6	3.7±0.7	5.56±1.23	60.0±15.0	2169	1^+

2. $\Lambda p \pi$ (I = 3/2, 1/2, Y = 1, B = 2, S = -1)

M (MeV/c^2)	Γ (MeV/c^2)	Significance ($N_{st.dev.}$)	$\sigma_{prod.}$ (μb)	Bag model predictions M (MeV/c^2)	Bag model predictions J^P
2495.2±8.7	204.7±5.6	12.86±1.68	70.5±15.0	2500	$0^-, 1^-, 2^-$

II. Strange exotic baryons-candidates for $\bar{q}q^4$-states

M (MeV/c^2)	Γ (MeV/c^2)	Significance ($N_{st.dev.}$)	$\sigma_{prod.}$ (μb)	Bag model predictions M (MeV/c^2)	Bag model predictions J^P
1704.9±0.9	18.0±0.5	5.3±1.6	19.0±0.6	1710	$1/2^-$
2071.6±4.0	172.9±12.4	10.3±1.5	88.0±27.0	2120	$1/2^-$
2604.9±4.8	85.9±21.5	5.2±1.4	31.9±9.0	2615	$3/2^-$

Again the candidates for six-quark Λp-dibaryons of 2183, 2255 and 2354 MeV/c^2 mass are clearly seen/51/. Further on these investigations will be continued on the spectrometers GIBS and RESONANCE, setups of the hybrid type anew being constructed.

The search for and study of multiquark states were also carried out in other experiments at the Dubna synchrophasotron.

So, over a period of several years the resonance states with isotopic spin 1=5/2 in systems $N\pi\pi$ have been searched for and studied in the experiment performed by Yu.A.Troyan's group/52/. Such states can be constructed of four quarks and one antiquark. The existence of this type of resonances was predicted in a number of theoretical papers[53], but numerous attempts to observe them experimentally had no success. In all these experiments charged particles were used as a primary beam. In the experiment of Yu.A. Troyan's group a beam of monochromatic neutrons with a momentum of (5.10 ± 0.17) GeV/c[54] was used which a 1m liquid hydrogen bubble chamber was exposed to. Such experimental conditions had a number of advantages: a) the absence of projectile charge allowed one to "load" the chamber in its exposure with neutron fluxes by an order larger than for charged particles; b) the possibility of separation of reaction $np \to p\pi^+\pi^+ n\pi^-\pi^-$, in which two isotopically conjugated states could be analyzed; c) a high monochromatization of neutrons made it possible to use standard methods of experimental data analysis and to compare the results of this experiment with other ones.

The search for and study of baryon resonances with I = 5/2 were accomplished by analysing the invariant mass spectra of systems $p\pi^+\pi^+$ and $n\pi^-\pi^-$ from reactions $np \to p\pi^+\pi^+ n\pi^-\pi^-$. In all 3088 events were used in the analysis. The method of experimental data processing and analysis is presented in[55]. The study of the invariant mass distributions of $p\pi^+$-system with respect to $n\pi^-$-system has shown that reaction $np \to p\pi^+\pi^+ n\pi^-\pi^-$ is "divided" into four subprocesses:

$$np \to p\pi^+\pi^+ n\pi^-\pi^- \qquad 13.6 \pm 8.2\%$$
$$\to \Delta_{33}^{++}\pi^+ n\pi^-\pi^- \qquad 30.5 \pm 8.0\%$$
$$\to p\pi^+\pi^+\Delta_{33}^-\pi^- \qquad 30.5 \pm 8.0\%$$
$$\to \Delta_{33}^{++}\pi^+\Delta_{33}^-\pi^- \qquad 25.4 \pm 8.0\%$$

In the analysis each of them was simulated by the corresponding phase space taking into account the peripherality of nucleons in reaction $np \to p\pi^+\pi^+ n\pi^-\pi^-$. Later on all experimental distributions were described by the four subprocesses added to the above weights. Final results are presented in fig. 16. In the figure are shown the invariant mass distributions of $\Delta\pi$ -combinations for different charge states. The $N\pi$ combination was assumed to be in the region of Δ_{33} isobar if its mass was within $1174 \leqslant M_N \leqslant 1254$ MeV/c^2. The solid lines represent the background from the above subprocesses. From the figure one can see that the invariant mass distributions of $\Delta^\circ\pi^-(\Delta^+\pi^+)$, $\Delta^{++}\pi^-(\Delta^-\pi^+)$-systems are well described by the background curves. The deviation from this description nowhere exceeds two standard errors. The invariant mass distributions of $\Delta^{++}\pi^+(\Delta^-\pi^-)$ - systems differ sharply from the background one. In this case there is a good agreement in the approximation of the experimental

distribution only by the curve being the sum of the background and three resonance curves with masses 1438, 1522, 1894 MeV/c^2 and widths 30, 20, 40 MeV/c^2. In fig. 16 the approximating curve is denoted by the dotted line. In this procedure the first resonance is described by the Breit-Wigner curve and the two other heavier resonances by Gaussian according to the experimental mass resolution which equals 9, 6, 11 and 23 MeV/c^2 in the region of corresponding resonances.

The total data on the observed resonances and corresponding predictions of some theoretical models are presented in Tables II and III.

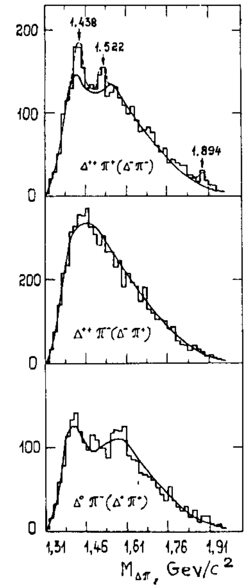


Fig. 16

Table II

M_{res}, MeV/c^2	Γ_{res}, MeV/c^2	σ (μb)
1438	23	9.9 ± 2.7
1522	$\leqslant 20$	4.8 ± 1.7
1894	$\leqslant 40$	3.3 ± 0.8

Table III

	M_{res}, MeV/c^2	Γ MeV/c^2	J^P	mode decay
	1438	23	$3/2^\pm, 5/2^\pm$	$\Delta\pi$
exp	1522	$\leqslant 20$	$1/2^\pm, 3/2^-, 5/2^+$	$\Delta\pi$, $N\pi\pi$
	1894	$\leqslant 40$	-	$\Delta\pi$, $N\pi\pi$
B.M.	2000	-	$5/2^-$	-
	1450÷1470	-	$1/2^-$	-
JSM	1550	-	$3/2^-$	-
	1900	-	$1/2^+, 3/2^+, 5/2^+$	-
SSR	1400÷1700	30 for M_{res}=1438	$5/2^+$.	$\Delta\pi$

The search for a possible manifestation of multiquark degrees of freedom in deuteron has been recently performed by the groups of L.S.Azhgirei (magnetic spectrometer, LCTA) and L.M.Strunov (ALPHA) in studies of inelastic scattering reactions of relativistic deuterons on different nuclei, i.e. processes $dA \to AX$, where A=p,d,C,..., have been investigated.

In the first experiment[56] deuterons having momenta of 4.3,

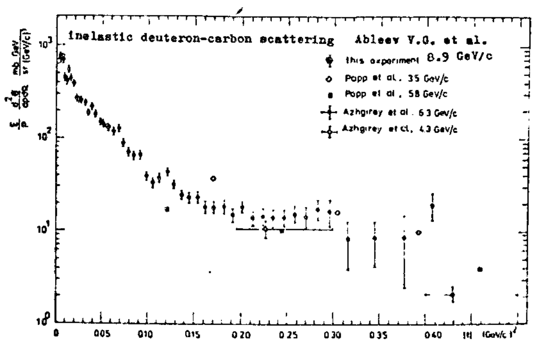


Fig. 17

6.3 and 8.9 GeV/c were scattered by target nuclei at an angle of 103 mrad so that the four-momentum transfer squared $|t|$ was $0.4(\mathrm{GeV/c})^2$ and achieved $2.5(\mathrm{GeV/c})^2$. In the second experiment /60/ deuterons having a momentum of 8.9 GeV/c were scattered at an angle of $\leqslant 0.4°$ so that the value of $|t|$ reached ~ 0.4 $(\mathrm{GeV/c})^2$.

Figure 17 presents the invariant inelastic scattering cross section of deuterons on carbon nuclei with the emission of detected deuterons "forward" versus $|t|$. In the same figure are presented the data of paper /57/, in which this reaction was studied for deuteron momenta of 3.5 and 5.8 GeV/c and a deuteron detection angle of 43.6 mrad.

The summary data in the figure show that the invariant cross section of reaction $dA \to dX$ with increasing $|t|$ changes much slower from $|t| \approx 0.2(\mathrm{GeV/c})^2$ up to $|t| \approx 2.5(\mathrm{GeV/c})^2$ than for $|t| < 0.2(\mathrm{GeV/c})^2$. A more detailed analysis of the deuteron spectra in the region of $|t| > 0.2(\mathrm{GeV/c})^2$ /58/ shows that there is a structure characteristic for excitation processes of nucleon resonances (see fig. 18). This fact

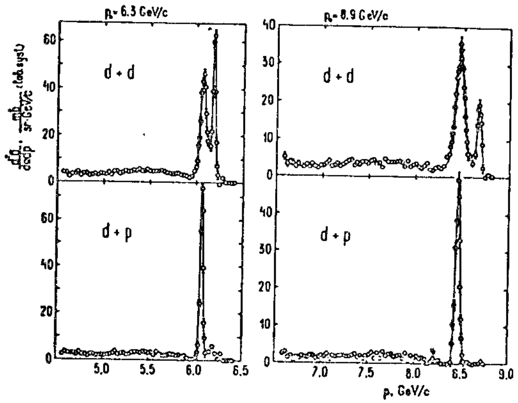


Fig. 18

means that the incident deuteron, to a large enough probability, loses a significant fraction of its momentum and does not "disintegrate" into individual nucleons. A possible explanation of this fact can be made within the frame of the quark model for elementary particles. Assuming that the deuteron has a quark structure and the

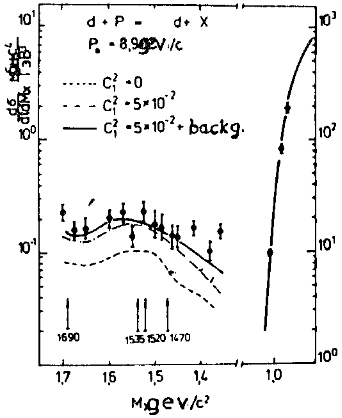


Fig. 19

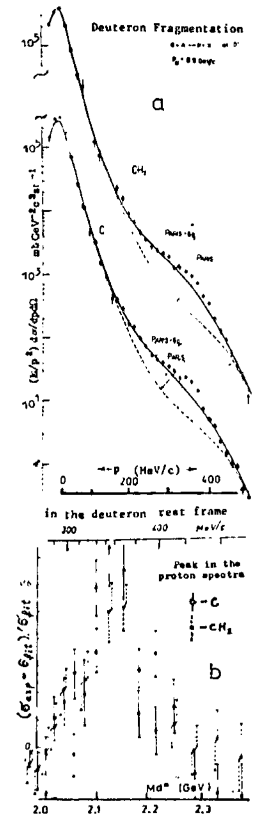


Fig. 20 a,b

multiple scattering of quarks of the incident deuteron on quarks of the target-nucleus makes a main contribution to the reaction cross section, the authors of paper /59/ reproduced correctly basic regularities of inelastic reactions $Ap \to AX$, where A=p or d. In particular, in order to describe the above results obtained by the group of L.S.Azhgirei, it was required to introduce the "hybrid" wave function of deuterons containing the contribution of six-quark state. In fact, as is seen from fig. 19 (solid line), the best agreement with experiment is reached if one assumes that in reaction $dp \to dX$ the dominating role belongs to excitation processes of nucleon resonances and to $\sim 5\%$ of six-quark admixture in the wave function of the incident deuteron.

The use of the hybrid wave function of deuterons allows one to interpret experimental results obtained by the group of L.N.Strunov /60/ in a study of the fragmentation process of deuteron with a momentum of 8.9 GeV/c on C and CH_2 targets at an angle of 0°. The yield of protons produced in reaction $dA \to pX$ was measured at emission angles of $\leqslant 0.4°$ over a momentum range of $-206 \leqslant p^*_{\parallel} \leqslant 580$ MeV/c (in the deuteron rest system). Results of the measurements are presented in fig. 20(a). Results of theoretical calculations made using different assumptions are given in the same figure. One can see that the experimental data confirm best the calculated results, in which the wave function of deuterons includes the contribution of 6-quark state. The estimate of the contribution of 6q-state, the root-mean-square of 6q-system and a relative phase of np- and 6q-components in the deuteron leads to the following values:

Type of target	Probability of 6q-admixture	$r(6q)$ fm	Phase of np- and 6q-components	χ^2/degree of freedom
C	$(5.4 \pm 0.6)\%$	0.99 ± 0.04	$(95 \pm 7)°$	1.6
CH_2	$(4.3 \pm 0.4)\%$	0.95 ± 0.05	$(82 \pm 6)°$	1.9

In fig. 20(a) it is also seen that an enhancement is observed over the range of proton momenta $295 \leq p^*_{\parallel} \leq 404$ MeV/c which is not used to measure the parameters of 6q-state. This enhancement can be due either to the process of dibaryon resonance production having a mass of (2.14 ± 0.01) GeV/c^2, a width of (80 ± 10) MeV/c^2 and I = 0 or to the process described by a triangular diagram with Δ -isobar in the intermediate state. The latter statement is hardly probable since, first, the width of the enhancement is more narrow as expected from the process with triangular diagram, and, second, for different targets the ratio of the cross sections $\frac{R(CH_2)}{R(C)} = 1.00 \pm 0.07$, where $R = \sum[\sigma^i_{exp} - \sigma^i_{fit}] / \sum \sigma^i_{fit}$, does not agree with the value which follows from isotopic invariance for the process with triangular diagram. This ratio should be ~ 2 for the effective number of nucleons ~ 4 inside the carbon nucleus. To check the first statement, the invariant mass spectrum of d*-system produced in reaction $dN \rightarrow d^*N$ and $d^* \rightarrow p + N$ was constructed (see fig. 20(b)). As is seen, a peak is really observed for $M_{d^*} \approx 2.14$ GeV/c^2. However, statistics is insufficient, and further studies are required.

Thus, the above-enumerated results of the experiments performed at the Dubna synchrophasotron confirm the existence of multiquark states in nuclei and nuclear processes and thereby open new possibilities for continuing studies (both experimental and theoretical) in this currently central field of elementary particle physics.

Hadronic bremsstrahlung radiation

In strong interactions of particles at high energies there occurs an essential change of the number of particle charges and momenta. This is the reason why bremsstrahlung γ-quanta should be observed along the trajectories of secondaries and along the beam forward direction. Energy and angular spectra of such γ-quanta depend on kinematic characteristics of primary and secondary particles. The energy spectrum of γ-quanta has a sharply falling form

of the dE/E type. At present there is in principle only one paper[61] devoted to the study of this effect in interactions of π^+-mesons with a hydrogen-neon mixture of the bubble chamber at 10.5 GeV/c. About 1% of hadron bremsstrahlung γ's were detected with respect to all γ's produced in these interactions.

Owing to a small detection efficiency for low energy γ's, the main fraction of γ's having $P_\gamma \lesssim 30$ MeV/c is not detected as e^+e^- pairs. Therefore the contribution of bremsstrahlung γ's from hadrons shows itself badly in the laboratory system as compared to background γ's from the decay of π^0-mesons. It is clear that bremsstrahlung radiation should have detailed kinematic properties in the laboratory and antilaboratory systems. However, energetic γ's in the laboratory system fall within the range of low energies in the antilaboratory system. The momentum spectrum of γ-quanta in the laboratory and antilaboratory systems has a characteristic shape with a maximum at 70 GeV/c and a decrease at $P_\gamma < 70$ MeV/c. Thus, due to methodical restrictions, this effect manifests itself well in the antilaboratory system.

Figure 21 presents the momentum spectra of γ-quanta produced in CTa interactions for 4.2 GeV/c per nucleon[62] in the laboratory (a) and antilaboratory (b) systems. The solid lines correspond to background γ's from π^0-mesons produced by Monte-Carlo using kinematic properties of π^--mesons. An excess of γ's is seen at $P_\gamma < 70$ MeV/c in the antilaboratory system. The momentum spectra of γ's for πp (a) and πC interactions at 40 GeV/c in the antilaboratory system are shown in fig.22[63]. Here the statistical material is more complete, and hence the experimental data are presented with a bin of 10 MeV/c. The dashed line corresponds to γ's from π^0-mesons. The contribution of hadronic bremsstrahlung radiation is clearly seen. It is about 5% of all γ's.

Thus, hadronic bremsstrahlung radiation is observed in hadron-hadron and nucleus-nucleus interactions.

IV. Conclusion

From the foregoing it follows

1) Relativistic nuclear physics as a new scientific field is successfully being develcped at JINR. For a relatively short period of time a great deal of results, the scientific significance of which is generally recognized, have been obtained in this field by physicists from JINR member-countries . In particular, extremely important information has been obtained on the properties of

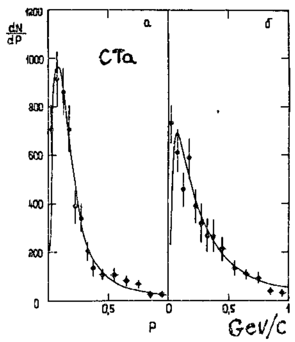


Fig. 21

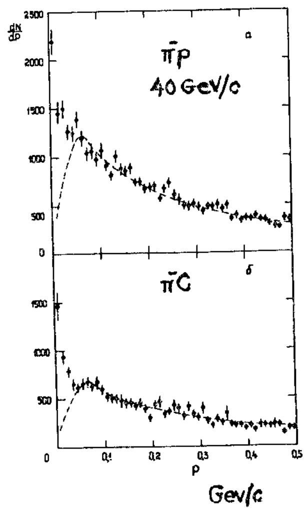


Fig. 22

nuclear reactions at small internucleonic distances and on the manifestation of multiquark degrees of freedom in nuclei and nuclear processes. First of all, this concerns the results obtained in the studies of nuclear reactions, in which the momentum significantly exceeding a Fermi nucleon momentum in the nucleus is transferred to atomic nuclei. This is the experimental confirmation of the hypothesis of cumulative effect and its features (locality of interactions, scale invariance, universality of characteristics of quark-parton structure functions of nuclei in the region of nuclear limiting fragmentation and so on), the observation of multiquark states in nuclei etc.

In addition, systematic investigations of multiple production processes of fragments and particles in interactions of relativistic nuclei (processes with small momentum transfers) allowed one to clarify a general picture (dynamics) of these processes and to confirm the validity of using the proton-neutron and the additive models for their description.

Finally, the search for "exotic" states not described by conventional quark models enables us to observe the existence of some of this type particles: dibaryon strange resonances, resonance state with isotopic spin 5/2 and so on.

2) The program of experimental research in the field of relativistic nuclear physics being performed at the Dubna synchrophasotron directly adjoins the problems of high energy and elementary particle physics, which are being solved on the largest accelerators, and is related to main problems of strong interaction physics: quantum chromodynamics and confinement.

The successful implementation of this program is a result of the conditions created for carrying out experiments at the Dubna synchrophasotron. In our opinion, a further development of the synchrophasotron as an accelerator of relativistic and polarized nuclei will allow physicists from JINR member-countries to carry out a broad range of present-day studies and to obtain results that will favour a further development of the theory of fundamental interactions.

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Экспериментальная программа исследований на синхрофазотроне ОИЯИ

В настоящем сообщении дается краткая информация о современном состоянии программы экспериментальных исследований, выполняемой на синхрофазотроне ОИЯИ в области релятивистской ядерной физики. При этом большое внимание уделяется описанию имеющихся в Лаборатории высоких энергий ОИЯИ уникальных возможностей для проведения исследований и обсуждению наиболее значимых физических результатов, полученных разными группами физиков ОИЯИ в последние годы в области релятивистской ядерной физики.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1982

Kuznetsov A.A. E1-82-660

Experiments at the Dubna Synchrophasotron

In this report we present a brief review of the current state of the program of experimental research at the Dubna synchrophasotron in the field relativistic nuclear physics. Some attention is being given to unique possibilities which we have at the High Energy Laboratory, JINR to carry out these studies and to the most significant physical results obtained recently by different groups of our physicists in the field of relativistic nuclear physics.

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

Preprint of the Joint Ins[illegible]

Перевод автора.