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A.M.Baldin

RELATIVISTIC NUCLEAR PHYSICS

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Балдин А.М.

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Физика релятивистских ядер

Дан обзор исследований, проводимых в ЛВЭ ОИЯИ в области релятивистской ядерной физики. Новые экспериментальные данные подтверждают выведенные ранее закономерности кумулятивного эффекта. Вместе с тем простейшие модели кумулятивного эффекта не смогли предсказать вновь обнаруженных особенностей углового распределения кумулятивных частиц. Первые данные по множественным процессам обнаружили возрастание с энергией (выше 2 ГэВ/нукл.) роли многобарионных столкновений. Обсуждается подобие характеристик столкновений релятивистских ядер в области нескольких ГэВ на нуклон и протон-протонных столкновений при энергиях в десятки и сотни ГэВ.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Relativistic Nuclear Physics

Review of the investigations carried out in the Laboratory of High Energies of JINR in the field of relativistic nuclear physics is given. New experimental data confirm the cumulative effect regularities obtained earlier. At the same time the simplest models of the cumulative effect haven't been able to predict recently discovered features of the angular distribution of cumulative particles. The first data on multiparticle processes revealed that the role of multibaryon collisions increases with energy (upper than 2 GeV/nucleon). The similarity of the characteristics of relativistic nucl. collisions in the region of several GeV per nucleon and proton-proton collisions at energies of tens and hundreds of GeV is discussed.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1978

In 1970 the Dubna synchrophasotron systems were adopted to accelerate light nuclei. This new stage in the accelerator development began wide experimental studies in a new scientific field, the relativistic nuclear physics.

The relativistic nuclear physics is assumed to mean a domain of many-baryon phenomena defined by the condition

$$\vec{p}^{\,2} \gg m^2 , \qquad (1)$$

where $\vec{p}^{\,2}$ are the squared three-momenta of particles, m^2 their mass squares. The condition (1) enables the asymptotics of the matrix elements to be considered. In this region the scale invariance is applicable which makes the theoretical treatment essentially simpler. It was already in 1971 that the first experiments with relativistic deuterons /1/ proved the validity of scale invariance as applied to composite nuclear systems. In the relativistic nucleus collision studies most attention was paid to the processes occuring in the range kinematically forbidden for collisions of free nucleons.

In experiments /1,2/ a process of collision of a relativistic nucleus with a target was discovered in which the energy transferred to the newly produced particles is much higher than the energy per nucleon of the nucleus (i.e., the energy of a group of nucleons is transferred to one particle). This effect was named by us cumulative.

In first discussions related to perspectives of the new trend sceptics asserted, and similar assertions still occur at present in literature, that the qualitative features of the processes due to relativistic nucleus collisions can be described by the Fermi motion of nucleons inside the nucleus, and a detailed description of them would turn out to be extremely complicated. Our optimism that the study of these collisions is capable of yielding a great deal of information was based on the following considerations:

(1) The extension of the ideas and methods of the physics of multi-particle processes intensively developed in high energy physics to relativistic nuclear collisions is not very difficult and gives necessary theoretical grounds for a constructive approach.

(2) A simple model based on the hypothesis that the collisions with large momentum transfers are defined by the local properties of hadron matter rather than the geometric characteristics of colliding objects, made it possible to predict the cumulative effect /4/. The possibility of studying the collision processes when there are present many particles not only in the final but also in the initial state enables us to employ both the statistical and hydrodynamical approaches more surely than this is done in the particle physics.

(3) In the diffractional scattering processes for which the ratio of the wave length to the size of a colliding object is of importance the transition to the study of nuclear collisions means for a given accelerator the transition to very high energies

$$kr \to zk\sqrt{2}A^{1/3}\, r,$$

z is the nucleus charge; k, the momentum; A, the mass number. For example, the elastic scattering of the Ne nuclei of an energy of 100 *GeV* available at the Dubna synchrophasotron by the Ne nuclei is expected to show diffractional phenomena similar to a pp scattering at an energy about 350 *GeV*.

Contrary to the particle physics, in the case of nuclei it is possible to vary the quantum numbers and the parameters of colliding objects in a wide range, their inner structure being known, at least, in a nonrelativistic limit.

(4) The study of multiquark states when quarks (partons) belonging to the group of nucleons are mixed can throw light on the problems of asymptotic freedom and quark confinement.

At the International Conference on High Energy Physics and Nuclear Structure in Santa Fe we gave a review[3] of the data accumulated by us in this field by the year 1975. The information about the cumulative effect (single-particle distributions) was by that time summarized as follows:

1. It was established a scale invariance in the limits of the existing accuracy.
2. The A dependence of the single-particle distribution in the fragmentation region of the nucleus was found to be in agreement with the predictions of the simplest model: A^m, where m increases with increasing cumulativity and reaches a value larger than unity.
3. The particular features of the form factor and the shape of the nucleus are nonessential for the cumulative meson production (the isotopes of various elements with essentially different number of neutrons as well as strongly deformed and spherical ones were studied).

The experiments were performed with relativistic deuterons and alpha particle beams. The data on limiting fragmentation of other nuclei were obtained on the basis of the idea of using the antilaboratory coordinate system: nuclear targets were bombarded by a proton beam and the produced particles were studied at an angle of 180° to the beam. This method is equivalent to the study of the cumulative meson production by nuclei up to uranium and is based on the limiting fragmentation hypothesis of Yang.

We consider inclusive reactions induced by collisions of nuclei I and II:

$$\mathrm{I} + \mathrm{II} \to 1 + \dots \text{ or } \mathrm{I} + \mathrm{II} \to 1 + 2 + \dots, \text{ etc.}$$

with the invariant distributions

$$\rho^{\mathrm{I}}_{\mathrm{II}}(1) = \frac{1}{\sigma_{in}} E_1 \frac{d\sigma}{d\vec{p}_1}; \quad \rho^{\mathrm{I}}_{\mathrm{II}}(1,2) = \frac{1}{\sigma_{in}} E_1 E_2 \frac{d\sigma}{d\vec{p}_1\, d\vec{p}_2}, \text{etc.}$$

Due to relativistic invariance ρ^{I}_{II} are the functions of the rapidity differences $y_i - y_j$, where $y_i = \frac{1}{2}\ln\frac{E_i + p_i^L}{E_i - p_i^L}$, E_i and $\vec{p}_i$ are the energies and momenta of the particles involved in the reaction. The Yang limiting fragmentation may be thought of as independence of ρ^{I}_{II} of $(y_I - y_{II})$. The experimental data on multiple particle production show that of importance are only short-range correlations in the rapidity space when $|y_i - y_j| < 2$. At $|y_I - y_{II}| > 2$, which corresponds to the energy per nucleon of the projectile higher than 3 *GeV*, ρ^{I}_{II} is factorized into two uncorrelated functions. One of them is defined in the region $|y_I - y_i|$ (i.e., the region of fragmentation of nucleus I) and the other in the region $|y_{II} - y_j|$ (i.e., in the region of fragmentation of nucleus II). The dependence only on $|y_I - y_i|$ or $|y_{II} - y_j|$ and the independence of $(y_I - y_{II})$ means scale invariance.

This consideration shows that for the study of the limiting fragmentation of, e.g., heavy nuclei it is not necessary to accelerate them. It is sufficient to study the particle production on these nuclei at angles close to 180°. In so doing, the properties of projectiles and even their energy (starting with a few *GeV/nucleon*) are nonessential. It seems obvious that the existence of the limiting fragmentation is not yet the evidence for the existence of the cumulative effect. The cumulative effect is the departure beyond the framework of the kinematics of one-nucleon collisions of while the limiting fragmentation is realized in the limits of it as well. The particular feature of the cumulative region of inclusive reactions is a sharp increase of the A dependence with increasing cumulative number. In the transition from the region of hadron fragmentation in hadron-nuclear collisions to the region of nucleus fragmentation the exponent m of the A dependence A^m changes more than by a factor of 10! The cumulative number is taken to mean the effective number of nucleons of a fragmenting nucleus. For one-particle distributions the minimal value of the cumulative number N is defined by the kinematic limits:

$$N^{min} = \frac{1}{m_p} \cdot \frac{m_{II}\, ch(y_I - y_{II}) \cdot m_1^{\perp} \exp(y_1 - y_I) + \frac{\Lambda^{min}}{2}}{m_{II}\, ch(y_I - y_{II}) - m_1^{\perp}\, ch(y_1 - y_I)} \Bigg|_{at |y_I - y_{II}| >> 1} =$$

$$= \frac{1}{m_p} (E_1 - p_1^L) ,$$

where $\Lambda = M_f^2 - m_I^2 - m_{II}^2 - m_1^2$

$M_f^2 = (p_I + p_{II} - p_1)^2$ is the squared missing mass. It may be expected that ρ is a rapidly decreasing function of N^{min}. It is worth noting that the simplest dependences like $\rho \sim \exp[-aN^{min}]$ describe satisfactorily not only the energy but also the angular dependences of the cumulative production of particles. The cumulative production of baryon systems is complicated by the presence of a single particle pole /3/ which is due to small binding energy of nucleons in the nuclei. In the region of the pole an one-particle distribution is factorized, depends only on $(y_I - y_1)$ and possesses angular distribution isotropy in the rest system of the fragmenting nucleus I.

However, as far as we move away from the pole, when $|y_I - y_1| >> 0.1$, the cumulative mechanisms become involved and then the dependence $\rho \sim \exp[-aN^{min}]$ describes satisfactorily the observed anisotropy.

The weak dependence of the cumulative effect on the properties of nucleus II is a simple consequences of the limiting fragmentation.

The creation at Dubna of nuclear beams of an energy higher than 3 *GeV/nucleon* and the discovery of the cumulative effect with unusual A dependences have resulted in wide investigations in a new scientific field-relativistic nuclear physics.

The aim of the present talk is to describe our understanding of these problems on the basis of the investigations which have recently been performed at Dubna.

THE MODELS OF THE CUMULATIVE EFFECT

The cumulative effect was predicted on the basis of the following assumptions

It is assumed that the invariant distributions of the produced particles

$$\rho^{I}_{II}(1)\,; \quad \rho^{I}_{II}(1,2), \text{ etc.},$$

in reactions $I + II \to 1 + \ldots$ or $I + II \to 1 + 2 + \ldots$, etc., where $E, \vec{p}$ are their energies and momenta, and σ_{in} the inelastic cross section, can be written in the form

$$\rho = \sum_N P_N \rho_N . \qquad (2)$$

Here P_N is the production probability for a group ("droplet") of N constituents (nucleons, quarks or partons), ρ_N are the invariant distributions describing the particle production due to the collision of this group with a target. The quantity P_N is found from the assumption that the constituents are moving independent of one another

$$P_N = \frac{A!}{N!(A-N)!} q^N (1-q)^{A-N} , \qquad (3)$$

A is the total number of constituents, q the probability for the constituent to fall within the volume occupied by a multinucleon cluster ("droplet"). This assumption about independent motion of constituents is in agreement both with the ideas of nonrelativistic nuclear physics and with the quark and parton models.

The second supposition was that the hadron-"droplet" collision can be described by the same ρ as that used to describe the collision between hadrons. It was based on the fact that the particle production cross sections in hadron collisions are weakly dependent on the quantum numbers of colliding objects. The distance at which the nucleons lose their individual features was taken to be $r \approx (0.6 \div 0.7) \cdot 10^{-13}$cm.The experiment had proved this estimate. The dependence of the cumulative effect on the atomic weight of the nucleus in the region of fragmentation is also satisfactorily predicted by eq. (3). To find this dependence we define q as the probability of finding of a constituent within a cylinder of a radius r and a weight equal to the thickness of nuclear matter on the path of the target:

$$q \simeq \left(\frac{r}{r_0 A^{1/3}}\right)^2 \sim \frac{1}{A^{2/3}} .$$

Substituting this q value in eq. (3) we have nontrivial A dependence

$$\frac{A!}{N!(A-N)!} q^N \approx \frac{A^{N/3}}{N!}\left(1-\frac{1}{A}\right)\left(1-\frac{2}{A}\right) \dots .$$

This corresponds to a strong increase of the A dependence with increasing cumulative number (approximately an additional form factor $A^{1/3}$ per each order of cumulativity). The probability P_N decreases very rapidly with increasing N, therefore it is natural to assume that the energy of the secondary particle defines the minimal N value allowed by the conservation laws. It follows from this consideration that in the region of cumulative particle production $\sigma_{in} \rho$ must depend on the atomic weight in an exponential manner A^m, where m increases monotonously with energy E_1 of the cumulative particle $m = \frac{2}{3} + \frac{E_1}{3\epsilon}$ (ϵ is the energy per nucleon of the relativistic nucleus).

In the range of the cumulative particle energy which is twice or three times as high as that per nucleon of the relativistic nucleus the power exponent must exceed unity. It was just this kind of dependence that was discovered in experiments of the Stavinsky /2,3/. A similar A dependence was found by the Cronin /5/ in experiments on production of particles with large transverse momenta $p_\perp$ by 300 *GeV* protons. They had observed a $A^{\alpha(p_\perp)}$ type dependence of the cross sections for these processes, $\alpha(p_\perp)$ is a monotonously increasing with $p_\perp$ function which exceeds unity at $p_\perp \gtrsim 2$ *GeV* outside the limits of errors. This analogy should be expected starting from the developed ideas about the effective interaction of nucleon group in the region of variables where the kinematics of the problem requires collisions with a massive object. The formulation of the problem in the case of the cumulative effect compared to the case of the large $p_\perp$ investigation has the advantage that in the former the regions kinematically forbidden for single-nucleon, two-nucleon and so on processes are explicitly selected. The question is often raised: is there a possibility of explaining the whole effect by the Fermi motion choosing appropriate wave functions at small internucleon distances and taking the relativism into account? It is obvious that the discussed A dependence can by no means be explained by the Fermi motion.

Nevertheless, possibilities of such a description of the cumulative effect are being discussed up to now /6/. At the same time it would be wrong to say that these dependences are quite clear. In particular, we have to clarify the relative role of the following two effects in the formation of a domain where the nucleons collectivize their partons up to the state of a "quark-parton plasma": whether this domain is due to compression of nuclear matter by the target inside the nucleus or it results from simultaneous interaction of a group of nucleons in a relativistically contracted nucleus. We can distinguish between these two effects experimentally. If the second effect plays the main role then unusual A dependences must arise only when the Lorentz factor $\gamma > A^{1/3}$. If the first effect is predominant the discussed A dependences of the cumulative particle production must also appear at $\gamma < A^{1/3}$.

A large amount of experimental information was analysed by Dar et al.[7] on the basis of the "coherent tube model". This model is a simplified version of the model defined by the formula (2). This simplification which was earlier suggested by Patashinsky[8] consists in the following:

$$\rho^{I}_{II} = \sum_{N} P_{N} \cdot \rho_{N}(s, y, p_{\perp}) \approx \rho^{p}_{II}(\langle N \rangle s, y, p_{\perp}),$$

where $\langle N \rangle \approx A^{1/3}$ is the average number of nucleons involved in the collision, $s = (p_I + p_{II})^2$, y is the rapidity and the superscripts p, II denote $p + II$ collision. At $s \to \infty$ the limiting fragmentation $\rho = \mathrm{const}(s)$ is valid and the A dependence in this model completely disappears. It seems dangerous to apply the simplified version in the region of high cumulativities where, according to eq. (2), the A dependence is predominant and should not disappear at $s \to \infty$. The idea to introduce the effective energy $s_{eff} = \langle N \rangle s$ *for* the description of the particle-nucleus collision was also suggested in ref.[9]. The main conclusion drawn from all these papers dealing with the simplified version of the model is that the large amount of experimental data available on multiple production of particles on nuclei and production of particles with large $p_{\perp}$ testifies in favour of the model of group interaction of the nucleons in the nucleus, that is in favour of the cumulative effect.

The model of the cumulative effect has recently been developed on the basis of the quark and parton approaches by Efremov[10] and Stavinsky[11]. In the above-mentioned formula $\rho = \sum_{n} C^{N}_{n} q^{n} (1 - q)^{N-n} \rho_{n}$ (n labels quarks) Efremov introduced for ρ_{n} an analytic expression obtained in a field theory model. The model gives a qualitative explanation of the characteristic features of the cumulative effect. Some particular development of this approach is given at the present Conference[12]. Stavinsky applied the model of the cumulative effect to the calculation of the properties of inclusive spectra in the case of infinitely large number of constituents. The merit of the model developed by him consists in that, in spite of the absence of free fit parameters, the description of a large amount of experimental data both on particle production by nuclei and in "elementary" hadron collisions is quite satisfactory. In the case under consideration we should go over from the summation to the integration. Eq. (2) takes then the form

$$\rho = \int_{N_{II}^{min}}^{A_{II}} P(A_{II}, N_{II})dN_{II} \int_{N_I^{min}(N_{II})}^{A_I} P(A_I, N_I)\cdot\rho(N_I, N_{II}, y, p_\perp)dN_I,$$

where $P(A,N)$ are the probability functions normalized to unity, P defines a fraction of the particle mass involved in the reaction $N_{II}m + N_I m \to 1 + ...$ In the general case ρ depends on all used variables, but in the calculation this function is taken to be equal to unity. For P it is assumed:

$$P = a(A)\frac{\exp[-a(A)\cdot N]}{1 - \exp[-a(A)A]}$$

the parameter $a(A)$ is defined by the average density "inside" the interacting hadron

$$\langle N \rangle = \int_0^A N\cdot P(N)dN = \frac{A}{\frac{4}{3}\pi R^3},$$

R is taken from the data on the elastic electron scattering. Thus, all the characteristic dependences of single-particle distributions are completely described by the reaction kinematics which defines the boundary values N_{II}^{min} and $N_I^{min}(N_{II})$. Specifically, the model explains the different yields of pions and antiprotons $(\frac{\bar{p}}{\pi} \approx 5 \cdot 10^{-3})$ in nucleon-nucleon collisions.

The above-mentioned experimental data and models provide only evidence for the existence of the cumulative effect and predicts its main features. It is quite clear that this is the very beginning of the investigation of a wast domain of new phenomena of the strong interaction physics.

As far as the quark structure of hadrons has over the past years given serious experimental grounds it would be natural to attempt to find effects which would surely reveal the quark structure of atomic nuclei. Among dynamical laws directly including the information on the structure of colliding objects of most importance is the law of scattering of composite particles at large angles discovered by Matveev, Muradyan and Tavkhelidze /13/ and given the name the quark counting rules.

The study of elastic scattering of nuclei at large momentum transfers makes it possible to verify this law when the number of constituents varies within a wide range. The question is especially interesting as to at what momentum transfers, at what relative spacings between the nucleons, the quark components assigned to individual nucleons are strongly mixed. As the above considerations show, this spacing should apparently be assumed to be 0.5 *fm*. That is, with increasing nuclear matter density by a factor of 5-10 there must proceed a transition of the nucleon liquid to a "quark plasma". The exact determination of the conditions of such a transition is of much importance for astrophysics. A very interesting estimation of the magnitude of the potential barrier defining the probability for the tunnel transition of a deuteron to a six-quark state was made by Matveev and Sorba /14/. It shows that the deuteron ground state contains a 3.5% admixture of states with "hidden colour". In other words, even for the description of a cold matter it is necessary to employ colour quarks and gluons. All these estimates show that at average spacings between nucleons of the order or less than 0.5 *fm* and average energies per nucleon of the order or higher than 2 *GeV* the transition of nuclear matter to "quark plasma" can occur. Such conditions appear to be realized in collisions of relativistic nuclei, and it is quite possible that the experimental material which is being accumulated by us will make it possible to study this transition. It may also clarify significantly the problem of the relativistic description of bound states /15,16,26/.

NEW EXPERIMENTAL DATA ON COLLISIONS OF RELATIVISTIC NUCLEI

The most complete and systematic studies of the cumulative effect were performed by the Stavinsky team who was first to discover the cumulative meson production effect in 1971. The existing theories of the cumulative effect give the qualitative desctiption of its main

Table

$$E\frac{d\sigma}{dP} \,/\, \mathrm{mb}\ \mathrm{GeV}^{-2}\, c^{3} \,/$$

$$\theta_{\pi} = 180^{\circ}$$

P_c/MeV	$P + P \to \pi + X$		$P + D \to \pi + X$		$P + He \to \pi + X$	
	π^+	π^-	π^+	π^-	π^+	π^-
150	11.3 ± 1.2		15 ± 1.3		45.5±3.4	
175	9.0 ± 0.6		10.1±0.55		34.6±2.6	
200	4.73 ± 0.3	1.42±0.26	6.6 ± 0.26	4.9±0,40	21.5±0,9	19.3±1.2
225	2.37±0.19		4.15±0.18		13.5±0.8	
250	1.77±0.12	0.55±0.09	2.50±0.09	2.40±0.10	7.95±0.43	7.3±0.52
275	1.14±0.09		1.70±0.08		4.85±0.3	
300	0.91 ±0.07	0.17±0.035	1.22±0.06	1.14±0.08	3.43±0.22	3.07±0.24
325	0.77±0.06		0.84±0.047		2.6±0.14	
350	0.235±0.048		0.475±0.039		1.55±0.13	
400			0.122±0.009	0.105±0.01	0,78±0.06	0.74±0.07
450			(2.7±0.19) 10^{-2}		0.256±0.018	
500			(0.78±0.10) 10^{-2}	(1±0.19) 10^{-2}	(3.4±0.75) 10^{-2}	(10±1) 10^{-2}
550			(1.8±0.87) 10^{-3}			
600			(0.54±0.51) 10^{-3}	(0.75±0.57) 10^{-3}	(1.13±0.14) 10^{-2}	(0.87±0.24) 10^{-2}

regularities. However, not all the laws which are important for the theory were studied experimentally. New experiments of the Stavinsky /17/ were devoted to first detailed measurements of the angular distributions of cumulative particles. To this end, a movable magnetic spectrometer was adjusted in a slow extracted beam of the synchrophasotron. The nuclei which were investigated in the region of their fragmentation were bombarded either by protons or by deuterons of a 8.6 *GeV/c* momentum. The secondary particles were detected in the range of angles from 80° to 180° to the primary beam. The data on the pion production cross section at

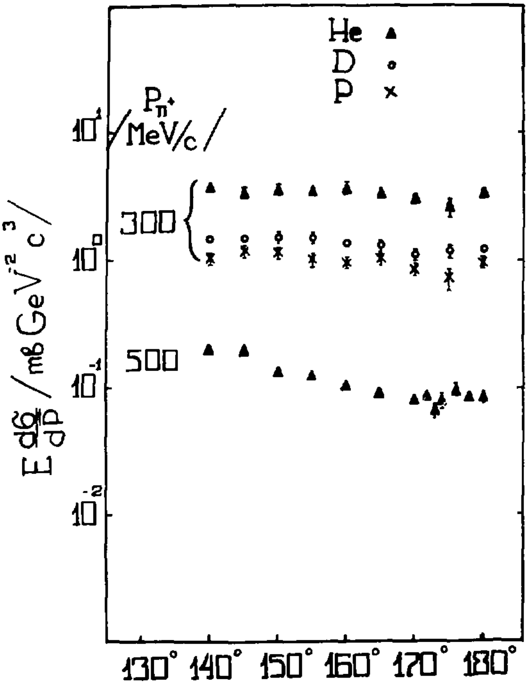

Fig. 1

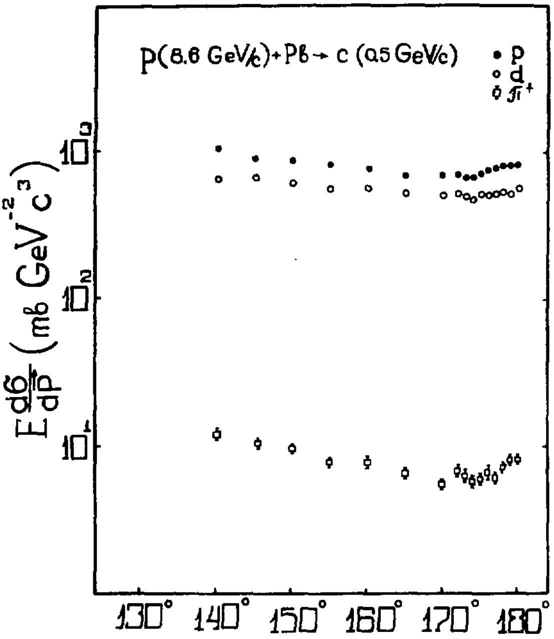

Fig. 2

an angle 180° when bombarding hydrogen, deuterium and helium targets by protons are given in the *Table* as functions of the pion momentum. The yield of positive and negative pions is practically the same for both deuterium and ^{4}He. The absolute value of the cross section for fragmentation of helium into pions three times exceeds that for fragmentation of deuterium into pions in the region of kinematical variables corresponding to the free nucleon collision. With increasing cumulative number this ratio increases exceeding 10.

Figure 1 gives the angular distributions of positive pions of an energy of 300 and 500 *MeV/c*. As is seen from the figure, the yield of pions of a fixed momentum depends very weakly on the angle of emission for all nuclei (P, D, ^{4}He).

Figure 2 presents the experimental data on the angular distributions of particles of 500 *MeV/c* momentum produced on lead nuclei by protons of 8.6 *GeV/c* momentum and *Figure 3* presents the same distributions by deuterons of 8.6 *GeV/c* momentum (i.e., with a momentum per nucleon twice as small as in the previous experiment). The statistical accuracy allows one to assume the presence of peaks in the angular distributions of heavy particles. These figures show, in particular, the invalidity of simple extrapolations to the angle of 180°. The existing simplest models of the cumulative effect make it impossible as yet to explain the details observed in these experiments.

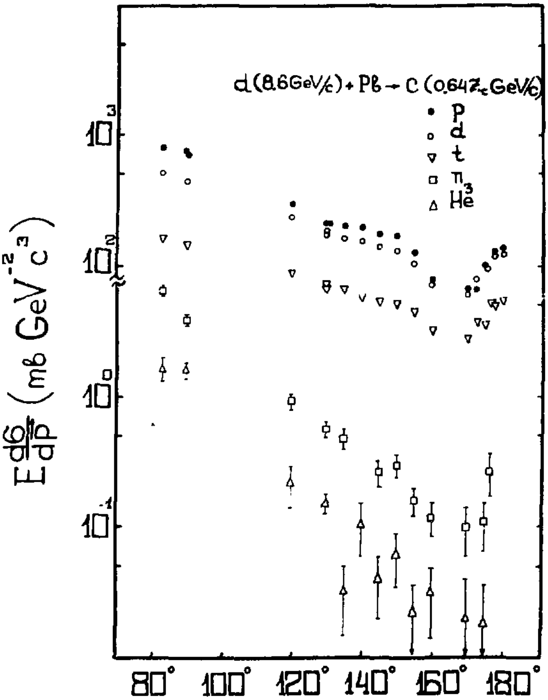

Fig. 3

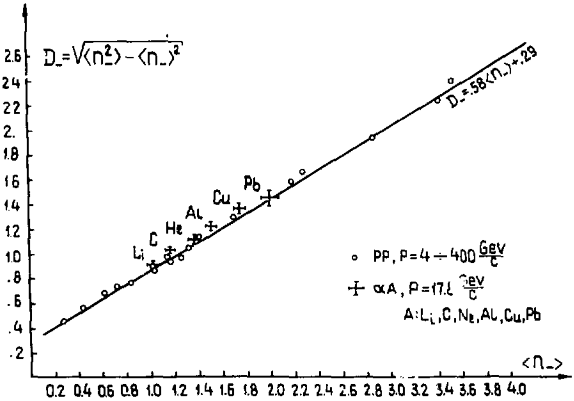

Fig. 4

First information on multiparticle production in collisions of relativistic nuclei has recently been obtained at Dubna. To this end, use is made of a 2 meter streamer chamber and a 2 meter propan bubble chamber. On the streamer chamber it was observed /18/ an interesting similarity of the multiplicity distributions of negative particles produced by 18 *GeV/c* alpha particles on the Li, C, Ne, Al, Cu and Pb nuclei and similar multiplicity distributions of negative particles produced in pp collisions at high energies. *Figure 4* shows the dispersion $D_- = \sqrt{\langle n_-^2\rangle - \langle n_-\rangle^2}$ of the multiplicity distribution of negative particles as a function of $\langle n_-\rangle$ for pp-collisions, there are also given the data on alpha-nucleus interactions at a 18 *GeV/c* momentum. The comparison of the multiplicity distributions for pp and alpha-nucleus interactions is given in *Fig. 5(a-f)*. The data are compared at the energy corresponding to $\langle n_-\rangle_{pp} = \langle n_-\rangle_{\alpha A}$. These figures well illustrate the assertion that the transition to the relativistic nucleus collisions is, in a certain sense, equivalent to the transition to high energies.

The Strunov team /19/ is performing investigations

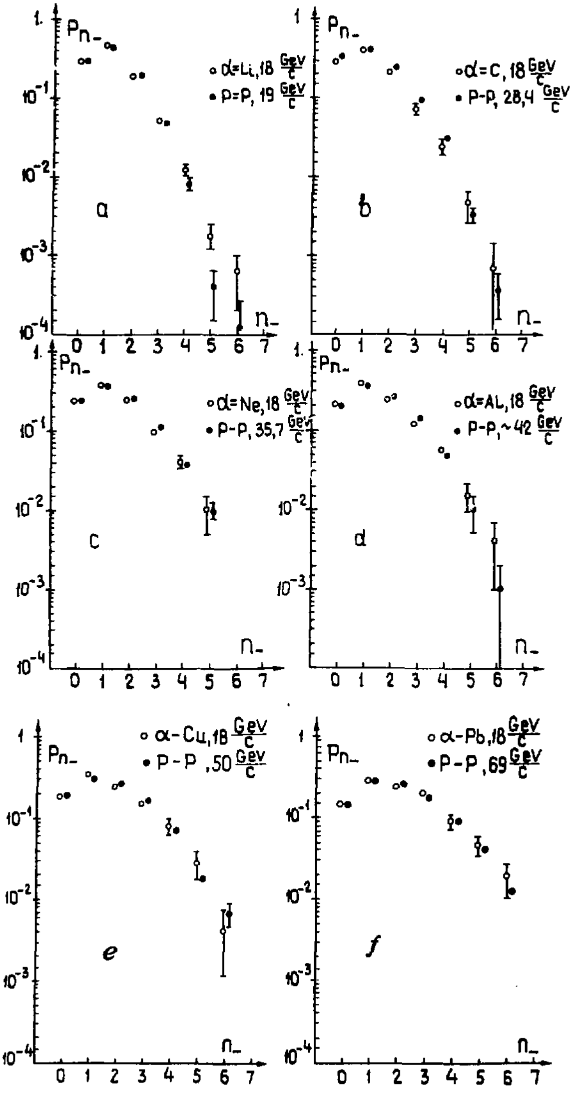Pn-
1.
10⁻¹
10⁻²
10⁻³
10⁻⁴
n-
0 1 2 3 4 5 6 7
a
○ α=Li, 18 GeV/c
● p=p, 19 GeV/c
b
○ α=C, 18 GeV/c
● P-P, 28,4 GeV/c
c
○ α=Ne, 18 GeV/c
● P-P, 35,7 GeV/c
d
○ α=AL, 18 GeV/c
● P-P, ~42 GeV/c
e
○ α-Cu, 18 GeV/c
● P-P, 50 GeV/c
f
○ α-Pb, 18 GeV/c
● P-P, 69 GeV/c

Fig. 5

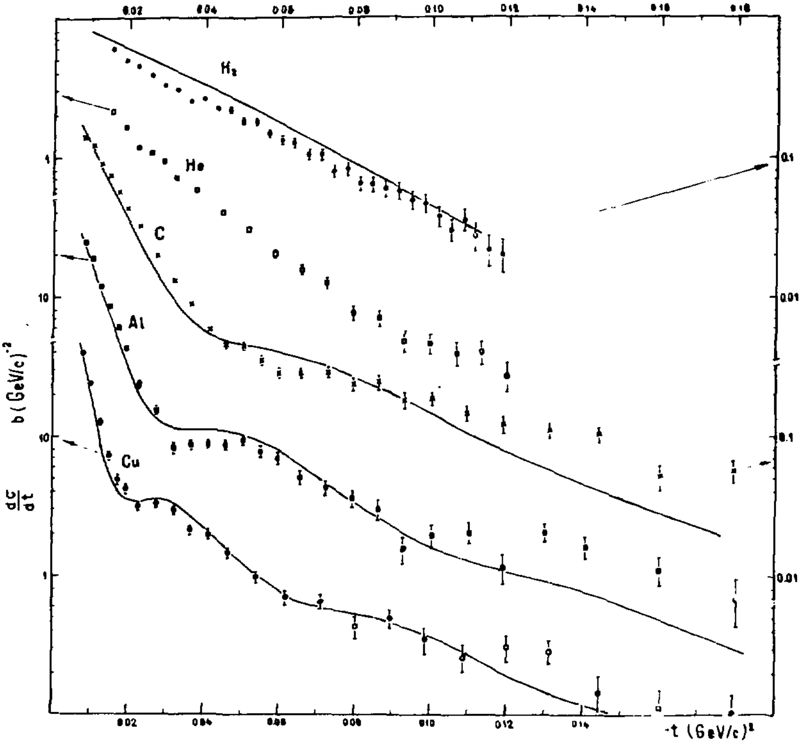

Fig. 6

with relativistic nuclei on a magnetic spectrometer with proportional chambers in which there has probably been detected oscillations of the differential cross section for elastic scattering of relativistic He nuclei as functions of the momentum transfer with respect to the average cross section value (see *fig. 6*). The oscillations of $d\sigma/dt$ were predicted by Tsarev[20] on the basis of a generalization of the diffraction dissociation theory suggested by him. Thus, the problem formulated in the particle physics had first been investigated in the relativistic nuclear physics.

The first results on elastic α-p scattering were obtained by means of a recoil nuclear spectrometer by the Nikitin team/21/ at an energy 1.75-4.13 *GeV/nucleon.* The cross sections were measured for small t: $0.003 \leq |t| \leq 0.05$ *GeV*^{2}/*c*^{2}. The He nucleus radius was found to be equal R = (1.37 ± 0.02) *fm*. This value coincides with the electromagnetic radius. The experimental method makes it possible to measure not only the slope parameter of the diffractional cone but also the ratio of the real to the imaginary part $\alpha = \frac{\mathrm{Re}\, f}{\mathrm{Im}\, f}$ of the scattering amplitude f, *fig. 7* shows the energy dependence of α. The curve is the calculation results obtained on the basis of dispersion relations. A discrepancy between theory and experiment at high energies is not of much significance since the theoretical results contain some uncertainties.

The results of irradiation of bubble chambers by relativistic nuclei /22/ are illustrated in *figs. 8,9* and *10*. *Figure 8* is a photograph of interaction of the ^{12}C nuclei

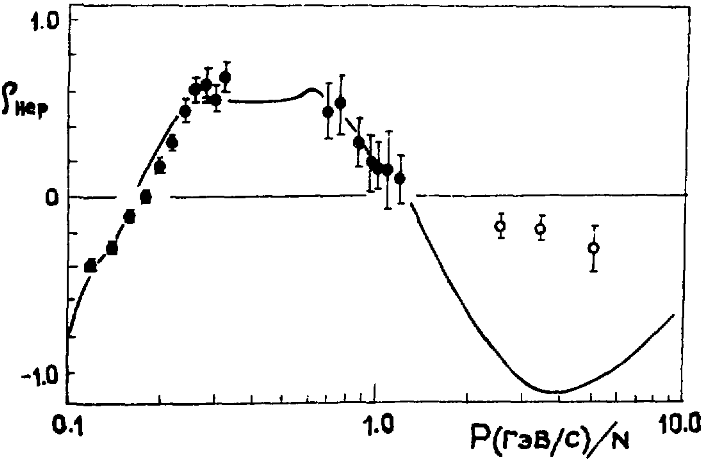

Fig. 7

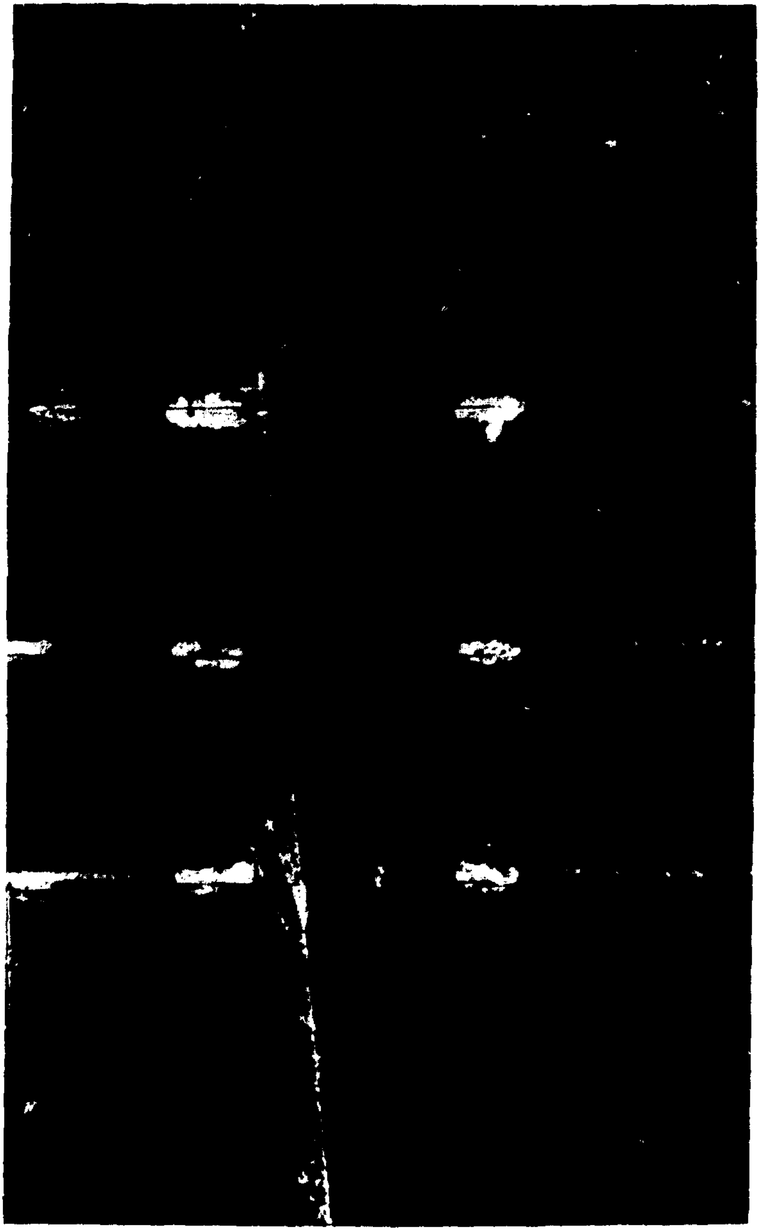

Fig. 8

with a momentum 50 *GeV/c* in the 2 meter propan chamber. The chamber contains three tungsten ($A = 184$) plates of (140x80x0.8) mm^3 dimension. The distance between neighbouring plates is 10 *cm*. The interaction of protons and the ^{4}He and ^{12}C nuclei with the tungsten nucleus were studied for three values of the projectile momentum per nucleon p_n. The table gives the π^- meson multiplicities obtained in these experiments as functions of p_n (*GeV/c*)

p_n	2.20	4.20	5.15	5.60
P W	0.14 ± 0.02	0.46 ± 0.04		0.69 ± 0.06
αW	0.53 ± 0.05	1.27 ± 0.09	1.56 ± 0.11	
αW(n_{st}=0)	0.57 ± 0.07	1.52 ± 0.15	1.98 ± 0.20	

The data for the events in which there are no stripping particles ("central" nuclear collisions) are given in the third line. The multiplicity growth is due to the increasing number of the nucleons of an alpha particle involved in the interaction. It is interesting to compare these data with the available in literature data on the π^- meson production in pp and np collisions:

p_n	2.20	4.20	5.60
pp	0.04 ± 0.01	0.18 ± 0.01	0.240 ± 0.005
np	0.220 ± 0.006	0.410 ± 0.012	0.520 ± 0.015

From the comparison it is concluded that at small momentum per nucleon $p_n = 2.20$ *GeV/c* π^- mesons are mainly produced in one-nucleon collisions. The multinucleon collisions become more important with increasing energy. The mutual influence of the nucleons of the alpha

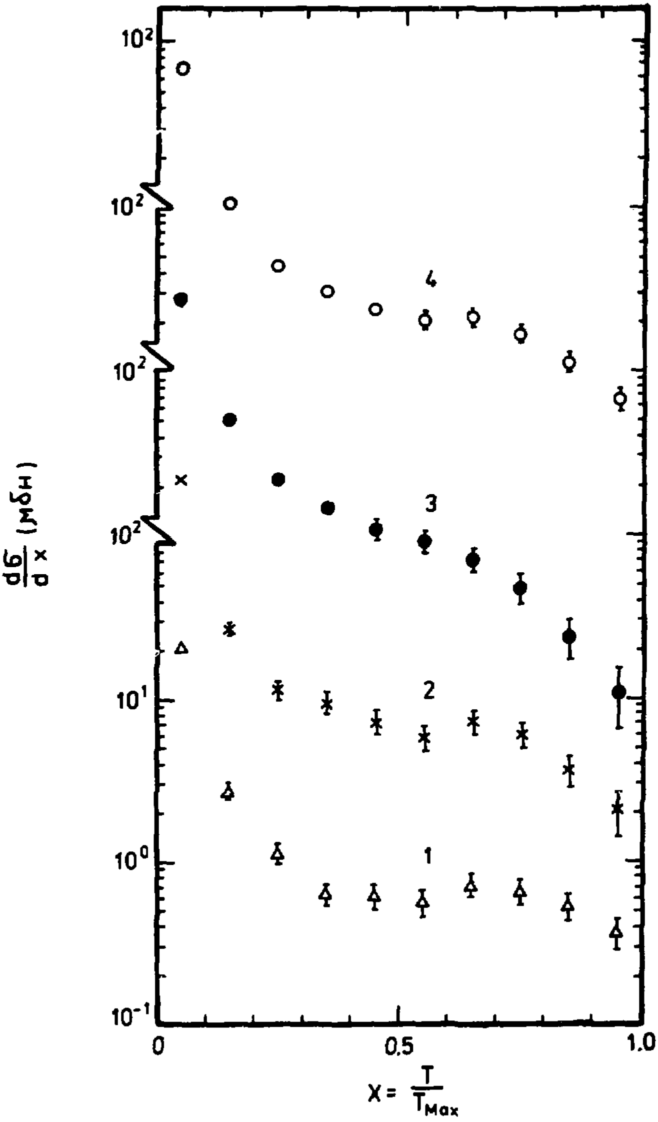
$\frac{d\sigma}{dx}$ (мбн)
10^2
10^2
10^2
10^2
10^1
10^0
10^{-1}
0
0.5
1.0
$X = \frac{T}{T_{Max}}$
4
3
2
1

Fig. 9

particle on the pion production process is also obvious.

An essential difference between the cumulative production mechanisms for mesons and baryons indicated earlier [23] suggests the study of the simplest process $dp \to ppn$ in more detail. Experiments on irradiation of the 1 meter hydrogen chamber by relativistic nuclei are performed on the synchrophasotron during many years. A partial description of them is given in the talk by Zelinsky [21] and the papers he refers to. The results of the $dp \to ppn$ experiments have recently been treated for the purpose of selecting the cumulative effect [25]. A large statistics enables us to reveal surely the region forbidden by the one-nucleon kinematics. The bubble chamber allows to study single-particle distributions under the conditions of 4π geometry. As the invariant variable $b_{I1} = \frac{(p_d \cdot p_1)}{m_d} - m_1$ was taken, where p_d, p_1, m_d, and m_1 are the four-momenta and masses of the deuteron and nucleon, respectively. In the deuteron rest system $b_{I1} = T$ is equal to the nucleon kinetic energy. *Fig. 9* presents the cross section $d\sigma/dx$ for the reaction $dp \to N + \ldots$ as a function of $x = T/T_{max}$ for different intervals of the angles of emission of the nucleons studied. The data are shown to cover all the range up to the kinematic limits of T_{max}. *Fig. 10* gives the invariant inclusive cross sections for production of neutrons (curve 1) and protons (curve 2) to the backward semi-sphere as functions of the invariant variable $b_{I1} = T$. Sharp break in slope in the range $b_{I1} = 0.02$ *GeV* shows the difference in the reaction mechanisms at small and large b_{I1} values. The cross section described by the pole mechanism (Fermi motion) is predominant but is concentrated in a narrow region of b_{I1} near zero. While, it is obvious that the region of large b_{I1} values (cumulative) is not described by the pole mechanism. The slope $1/T_0$ in this region for the approximation $B\exp[-\frac{T}{T_0}]$ is in agreement with that extracted from experiments [23] on large-angle proton production on nuclei. The data obtained show that the cumulative effect has a rather large cross section so that it can be studied by means of bubble chambers. Of special interest is the investigation of the influence of the final state interaction on the cumulative particle production. First results of such an investigation show that the interaction in the final state of the two other nucleons in the reaction $dp \rightarrow p(pn)$ strongly affects the high-energy part of the spectrum of the separated nucleon.

CONCLUSIONS

1. At Dubna a large programme of investigations with relativistic nuclei up to ^{20}Ne of an energy up to 5 *GeV/nucleon* is being performed/27/. The intensities of the extracted beams/25/ are emough to carry out studies with the aid of the existing methods of high energy physics. Four electronic detectors, 2 meter streamer chamber, 2 meter propan bubble chamber with metallic targets and 1 meter liquid hydrogen chamber are used.

2. The inclusive single-particle distributions for particles produced in relativistic nucleus collisions which have been studied since 1970 have large values in the region of nuclear fragmentation kinematically forbidden for one-nucleon collisions. The discovered A dependences and scale invariance exclude completely the possibility of explaining the relevant experimental data by means of the Fermi motion and are in agreement with the predictions based on the hypothesis about the existence of the cumulative effect.

3. The models of the cumulative effect earlier suggested and recently developed explain qualitatively its main laws. The existing ideas make it possible to discuss the experimental data on the basis of a collectivization of parton-quark constituents of individual nucleons. New experimental data require an essential quantitative development of the models available.

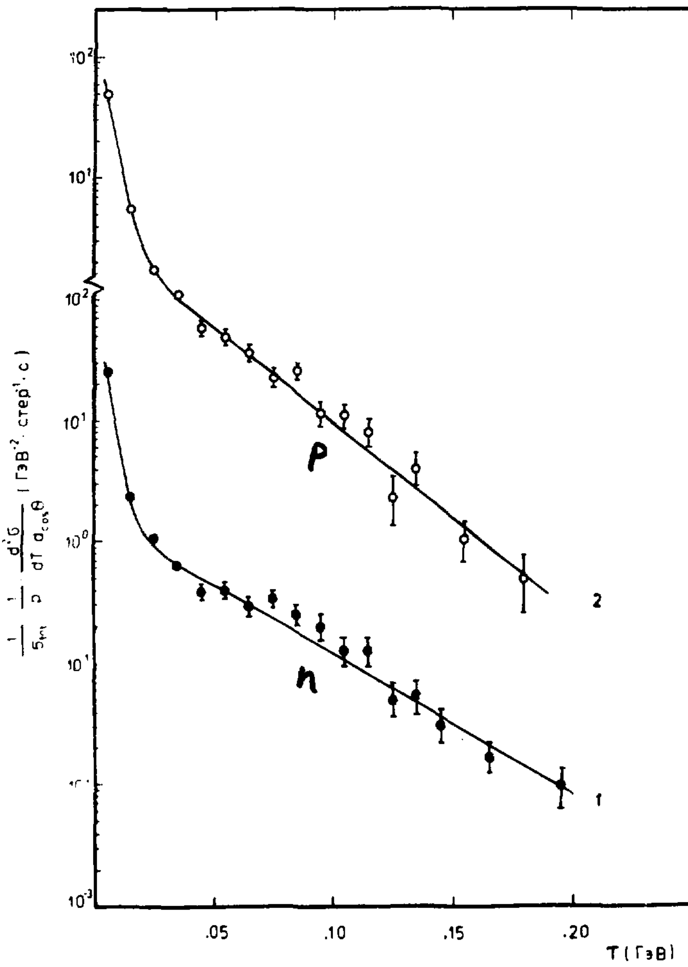

Fig. 10

4. The study of multiparticle processes occuring in relativistic collisions of nuclei has demonstrated the great role of many-baryon collisions which is ever-increasing with energy per nucleon. Attention should be paid to the analogy of the characteristics (multiplicity distribitions, diffractional scattering) of nuclear collisions at an energy up to 5 *GeV/nucleon* and elementary particle collisions of energies of some dozens and hundreds of *GeV*.

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