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CUMULATIVE EFFECT AND PROCESSES OF MULTIPLE PARTICLE PRODUCTION

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Introduction

Cumulative effect is the process of collisions of particles or nuclei with target-nucleus in the region of limiting nuclear fragmentation (E ≥ 3.5 GeV per nucleon) where scale invariance is valid. As a result of this, the momentum, which is much larger than that per nucleon of the nucleus, is transferred to the particle produced. The hypothesis of the cumulative effect was first advanced by A.M.Baldin in 1971 /1/. Underlying a quark-parton level of the phenomenon, the concept of the cumulative effect naturally includes ideas of locality of hadron interactions as large momentum transfers and the fact that a point-like obgect with momentum larger than that of the whole nucleon belongs to a group of nucleons of the nucleus. This means that for processes of this type the notion of nucleon as a "good" quasiparticle makes no sense, and its internal structure should be taken into account.

Such important properties of the cumulative effect as scale invariance of inclusive spectra of hadrons and enhanced A-dependence of their production cross sections were found already in first experiments carried out by V.S.Stavinsky's group at the Dubna synchrophasotron with relativistic deuterons.

In a number of subsequent experiments /2,3/ V.S.Stavinsky's group has studied in more detail the indicated properties of nuclear reactions versus scale variable X /4/ $(0.25 \le X \le 3.5)$ and variable $P_\perp$ using beams of protons and deuterons and a large set of target-nuclei (from Li to U). The following facts have been established.

- For energies of relativistic particles/nuclei ≥ 3.5 GeV per nucleon there is an asymptotic regime (limiting nuclear fragmentation region) in which the dependence of invariant cross sections for reactions of the type I + II → 1 + ... on specific relativistic-invariant energy ϵ of colliding objects and other variables, except the ratio of scalars $(P_{II}P_1)/(P_{II}P_I)$, is insignificant. Here

$$\epsilon = (P_{II}P_I)/m_I m_{II}\,,\quad (P_{II}P_1) = m_{II}\sqrt{m_1^2 + P_{1\perp}^2}\; ch\,(y_1 - y_{II}),$$

$$(P_{II}P_I) = m_I m_{II}\; ch\,(y_I - y_{II}),\quad y_i = \frac{1}{2}\ln\left[(E_i + P_{iz})/(E_i - P_{iz})\right]$$

and P_{iz} is the projection of particle momentum on the reaction axis. The value of boundary energy E ≥ 3.5 GeV/nucleon follows from the property of short-lived correlations in rapidity space. According to this value, the radius of the correlations, Δy, found in experiments on multiple particle production in hadron interactions, is approximately 1-2. Hence for

$$(P_{II}P_I) \approx m_I m_{II}\, ch\,\Delta y$$

the specific energy is ~3.7 what just corresponds to the energy of incident particle ~3.5 GeV/nucleon.

- There are a strong dependence of invariant cross sections of cumulative hadron production on the degree of cumulativity (or variable X) and a weak one on the flavour of hadrons. For X from 0.6 up to 3.5 this dependence (see fig.1a) is well described by a single exponential function of the type

$$E_1\frac{d\sigma}{d\bar{p}_1} = Const\; A_I^{1/3} A_{II}^{n(x)} \exp\left[-\frac{x}{\langle x\rangle}\right] \approx G(x)\,\varphi(P_\perp^2)$$

with universal slope parameter $\langle X\rangle = 0.14$ and function

$$G(x) = Const\; A_{II}^{n(x)} \exp(-x/\langle x\rangle).$$

Here A_I and A_{II} are the atomic weights of colliding objects and n(X) is equal to 2/3 + X/3 for X < 1 and 1 for X > 1 /5/ and the function $\varphi(P_\perp^2)$ obeys the following relation /6/

$$\varphi(X) = 0.9\exp(-2.7\,P_\perp^2) + 0.1$$

- For equal values of variable X invariant cross sections of cumulative pion and kaon production obey, within experimental errors, the following relation

$$E_1\frac{d\sigma}{d\bar{p}_1}(\pi^+) \approx E_1\frac{d\sigma}{d\bar{p}_1}(\pi^-) \approx E_1\frac{d\sigma}{d\bar{p}_1}(K^+) \gg E_1\frac{d\sigma}{d\bar{p}_1}(K^-).$$

- For large values of A_{II} and X > 1 there is an enhanced (as compared to $A^{2/3}$) A_{II} -dependence of production cross sections of cumulative particles.

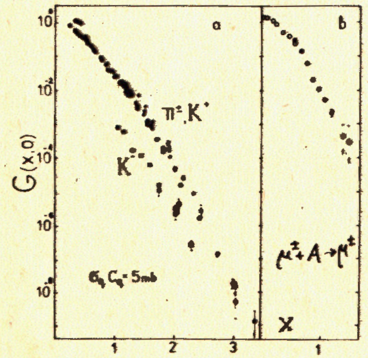

Fig. 1

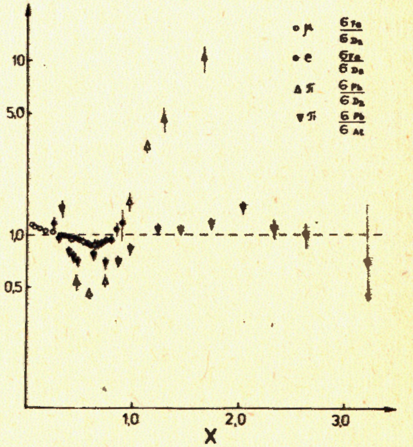

Fig.2a

The above regularities of the effect have been studied and supported for different types of interactions over a broad range of energies. Primarily this relates to experiments carried out by the groups of G.A.Leksin /7/, K.Shaginian /8/ and L.Schröder /9/.

Thus, an experimental test of the cumulative effect carried out in systematic studies of inclusive nuclear reactions with large momentum transfers in the region of limiting nuclear fragmentation 1) confirmed the existence of this physics phenomenon, 2) established the universality of its principal properties and 3) indicated a quark nature of cumulative processes.

These results led to the necessity of introducing new (for nuclear physics) ideas of the quark structure not only of nucleons but also of nuclei. In particular, by analogy with "hard" hadron-hadron interactions, the conception of quark-parton structure functions of nuclei as independent (not reducible to one-nucleon) objects of hadron physics was introduced. In this case, e.g., the longitudinal distribution of quarks in the nucleus and in the region of cumulative effect is determined by the structure functions G(X). When $X > 1$ and $P_\perp^2 = 0$, they characterize the probability that a constituent carries the momentum of a group of nucleons of the nucleus.

The properties of the structure functions found in experiments on limiting nuclear fragmentation were the first to show evidence for the existence of multiquark configurations in nuclei which are significantly different from those in free nucleons and multinucleon systems /10/.

The same results allowed A.M.Baldin /11/ to make concrete predictions concerning not only the behaviour of deep-elastic scattering cross sections of leptons on the nucleus but also their absolute values. An experimental check of this prediction was first carried out in NA-4 experiments of the JINR-CERN collaboration /12/ where the deep-elastic scattering of μ^--mesons on carbon nucleus was studied for an energy of 280 GeV in the interval of momentum transfers ≥ 50 GeV/c^2. As seen from fig.1b, the behaviour and characteristics of the structure function of carbon nucleus $F_2(X)$ obtained in these experiments are similar to those found previously in the experiments on limiting nuclear fragmentation.

The properties of the structure nuclear functions have been also confirmed in recent experiments on the deep-inelastic scattering of μ-mesons /13/ and electrons /14/ on D, Fe nuclei performed respectively by the groups from CERN and SLAC. The results of these experiments and the data obtained by V.S.Stavinsky's group are shown in fig.2a. One can see that in the overlapped range of X values (i.e. in the range $X > 0.3$) the CERN and SLAC data are in good agreement with the Dubna ones obtained from the experiments on limiting nuclear fragmentation. Besides, as seen from the figure, the Dubna results give new information on the properties of the structure nuclear functions in the range of large X, not yet studied in lepton-nucleus interactions, and on the properties of the structure functions for other nuclei /15/.

The above behaviour of the ratios of the structure functions for different nuclei directly indicates the existence of multiquark configurations in nuclei realized by a group of nucleons inside the nucleus with effective number X which are substantially distinct from multinucleon systems in a free state. In this case cumulative processes can be considered as a result of the interaction of quarks from the incident object with this type of multiquark configurations in the target-nucleus. Therefore the data of fig.2a,b can be naturally interpreted as the presence of a significant difference in multiquark configurations of D and Pb nuclei and the existence of their weak difference for Al and Pb nuclei. Taking into account this fact and also the data on the A-dependence of the ratio of structure functions for other nuclei at fixed variable X(e.g., $X = 1.3$) obtained

by the group of V.S.Stavinsky /15/, one can expect (see fig.2c) that there are possible multiquark configurations not only for deuterium but also for other light nuclei with $A < 20$ which differ from one another. This difference should be stronger for a larger difference of A value of nuclei /19/.

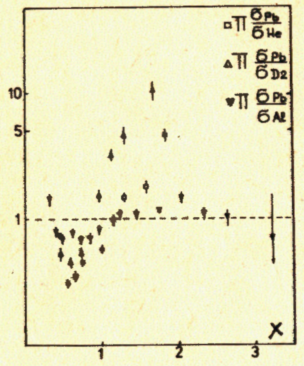

Fig. 2b

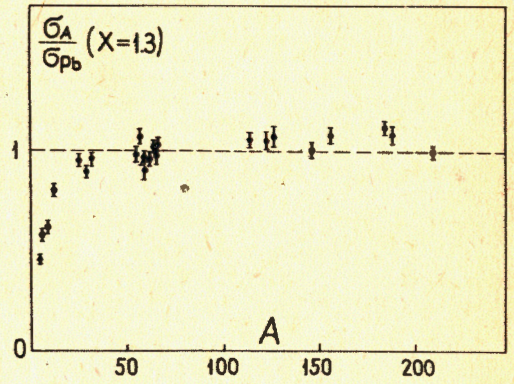

Fig. 2c

1. Multiple particle production processes in cumulative h + A interactions

The result of the experimental test of the consequences of the cumulative effect discussed in the introduction have been obtained in the studies of inclusive reactions. However, to obtain more extensive information on the dynamics of cumulative processes, it is of extreme importance to know main properties not only of cumulative particles but also of particles "accompanying" their production.

An attempt to study cumulative processes in other than inclusive experiments have been carried out by several groups from the Laboratory of High Energies, JINR using pictures from the 2m propane bubble chamber /16-17/.

1.1. Properties of cumulative pions and protons produced in hadron-nucleus interactions at 10 and 40 GeV/c

Below we shall discuss results of a study of multiple production processes in πp (40 GeV/c) and pC, pTa (10 GeV/c) collisions accompanying the production of cumulative pions and protons.

The processing and analysis of the results can be found in /18/.

Cumulative events were selected as follows: events were assumed to be cumulative if in them there was at least one pion or proton emitted at an angle of $\geq 135°$ in the lab. system and having $\beta_0 \geq 0.4$ for pion and $\beta_0 \geq 1.3$ for proton. Here the cumulative number $\beta_0 = X = (E_i - P_{i\parallel})/m_N$; E_i and $p_{i\parallel}$ are the total energy and momentum of secondary particle in the lab. system and m_N is the nucleon mass. A physical validity of the selection of such values for angle and variable β_0 is described in detail in paper /16/. It is based on the fact that the indicated values of X are boundary for the behaviour of general characteristics (average multiplicity, average momentum, average emission angle in the lab. system and average rapidities) of cumulative particles versus X with respect to all accompanying particles produced in pC and pTa interactions at 10 and 40 GeV/c, respectively.

Main properties of the indicated general characteristics of charged particles produced in pC and pTa interactions at 10 GeV/c are the following:

- there is an enhanced A-dependence of the production cross sections of cumulative pions and protons. The value of

$$n = (\ln \sigma_1/\sigma_2)/(\ln A_1/A_2)$$

is $1.44 \pm {}^{0.04}_{0.03}$ for cumulative protons and $1.13 {}^{+0.03}_{-0.06}$ for cumulative pions.

- the events, having cumulative protons, are accompanied, as a rule, by an increased multiplicity of all protons, and the events, having cumulative pions, by an increased multiplicity of all pions. For instance, the ratios $R_{p/\pi}$ of the average multiplicity of accompanying protons in the events with cumulative protons($\langle n_p \rangle_{cum}$) or accompanying pions in the events with cumulative pions ($\langle n_\pi \rangle_{cum}$) to the average multiplicity of emitted protons or pions ($\langle n_{p/\pi} \rangle_{all}$) for all pC and pTa events are equal to: $R_p = 1.57 \pm 0.07$, $R_{\pi^+} = 1.28 \pm 0.09$, $R_{\pi^-} = 1.30 \pm 0.08$ (for pC collisions) and $R_p = 1.53 \pm 0.08$, $R_{\pi^+} = 1.42 \pm 0.13$, $R_{\pi^-} = 0.99 \pm 0.11$ (for pTa).

- all average characteristics (except multiplicity) of secondary particles in interactions with cumulative proton production have no distinct differences in comparison with the characteristics in interactions with cumulative pion production. For example, the ratios of the indicated characteristics, within experimental errors, are equal to unity.

In addition, within the available statistical accuracy, no dependence of these characteristics on cumulative number β_0 is observed both for protons and for pions.

- the general characteristics of "leading" protons and pions (i.e. particles having $x = P^*_{\parallel}/P_{max} > 2$ in the NN c.m.s.), accompanying the production of cumulative protons and pions, are invariable versus cumulative variable β_0.

- the dependence of the invariant inclusive cross sections for cumulative protons and pions in pC and pTa collisions on variable Q = X-B (X is the cumulative number of the hadron considered and B its baryon number) shows their universal behaviour: these dependences have an exponential form with universal constant $\langle X \rangle = 0.14$ (see fig.3).

Besides, the dependence of the invariant inclusive cross sections of cumulative protons on their momentum squared also has an exponential form with slope parameter when approximating by the expression $\approx \exp(B P_\perp^2)$ with $B = 15 (GeV/c)$ for pC and pTa interactions.

All the above general characteristics of secondary particles produced in pA collisions at 10 GeV/c coincide, within experimental errors, with the π^-C results obtained previously at 40 GeV/c [16]. The correlations under discussion have been also observed for proton production in pion-nucleus interactions at momenta of 3,7,6, and 9 GeV/c [20], in γ + A interactions [21], and in neutrino/antineutrino-nucleus collisions [22]. All these facts confirm the universality of the general characteristics for the processes of cumulative hadron and accompanying particle production in hadron-nucleus interactions although invariant specific energies differ by a factor of > 30.

1.2. Hadron jets in cumulative π^-C interactions at 40 GeV/c

The analysis of multiple hadron production in different processes, such as e^+e^- annihilation, deep-inelastic lepton-hadron collisions and soft hadron-hadron interactions, has shown that the production of hadron jets, which have a number of universal properties, is observed in these interactions. Collective characteristics of the jets, "sphericity", "thrust" and others, the multiplicity of hadrons and their momentum distributions in the jets coincide for these processes at equal energies in the c.m.s. The observed similarity of the properties of hadron jets is probably due to the existence of a single mechanism of quark hadronization for soft and hard interactions [23].

It is of interest to study the properties of hadron jets produced in hadron-nucleus collisions which can give information on the influence of nuclear matter on their formation and will allow one to establish more general regularities of quark hadronization for different types of interactions.

Cumulative processes are of principal interest. In this case quark-parton structure functions, determined due to multiquark states in nuclei, are obtained from data on limiting nuclear fragmentation ($E \geq 3$-4 GeV).

Quark hadronization from multiquark nuclear states is practically unstudied. Therefore it is particularly interesting to select jets in the region of nuclear fragmentation and to compare them with the properties of hadron jets in e^+e^- and hadron-hadron interactions.

Figure 4 presents possible diagrams of the fragmentation production of hadron jets for π^-p, e^+e^- and cumulative π^-C interactions. The analysis carried out in [24] has shown that the production of two hadron jets in π^-p interactions, collimated towards an incident pion and in an opposite direction, can be mainly considered as a result of the fragmentation of noninteracting $\bar{u}$(d) quarks (forward hemisphere in the c.m.s.) and uu(ud) diquarks (backward hemisphere in the c.m.s.) from primary particles. Similarly, the production of secondary particle jets in the c.m.s. of π^-C interactions can be presented as a result of the fragmentation of noninteracting u(d) quarks from incident π^--meson in the forward hemisphere and as a result of quark fragmentation from multiquark states of carbon nucleus in the backward hemisphere (region of target-nucleus fragmentation).

In this paper we discuss the fragmentation of quarks and diquarks into charged pions, neutral strange K -mesons and Λ^0-hyperons and collective characteristics of jets.

Experimental data have been obtained using the 2m propane bubble chamber exposed to a beam of 40 GeV/c π^--mesons at the Serpukhov accelerator. The work was done on statistics of 6480 π^-C interactions*) in which charged pions and protons were measured (the latter were identified over a momentum range of $200 \leq P_{lab} \leq 800$ MeV/c). 550 K^0-mesons ($K^0 \to \pi^+\pi^-$) and 294 Λ^0-hyperons ($\Lambda^0 \to p\pi^-$) were also used in the analysis. 11688 inelastic π^-p interactions with 753 K^0-mesons and 345 Λ^0-hyperons were used to compare with the π^-C data.

The method of selection of π^-p and π^-C interactions, the identification of neutral strange particles and a further processing of the events are described in detail in papers [25].

*) Pion interactions with quasi-free nucleons were excluded.

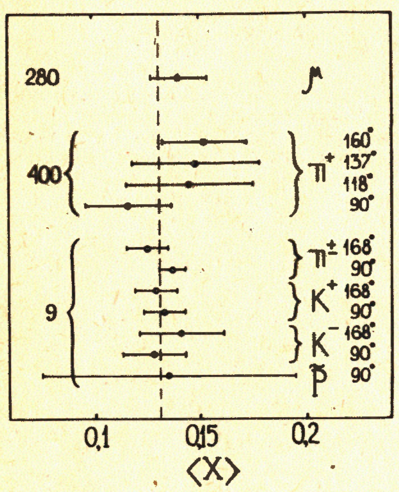

Fig.3

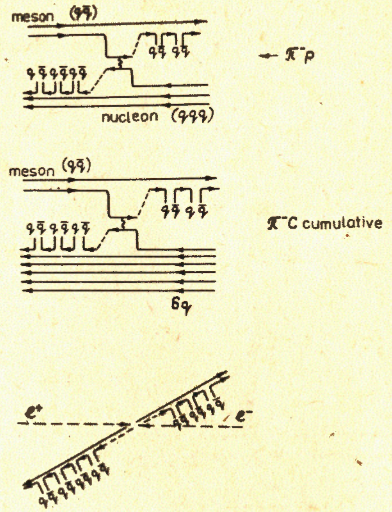

Fig. 4

Multinucleon π^-C interactions with the total charge of secondary particles $Q = N_+ - N_- \geq +1$, where N_+ and N_- are the numbers of secondary positive and negative particles per interaction, were selected for the analysis. In this case the protons having $P_{lab} \leq 300$ MeV/c were excluded as in this region the fraction of spectator protons of the target-nucleus is large. For each group of multinucleon π^-C interactions with charge Q the analysis was performed in the c.m.s. of incident π^--meson and the corresponding number of nucleons (ν_n) involved in the interaction. In the events with Q = +1 there were two interacting protons, with Q = +2 three protons and so on. As neutrons also participate in these collisions, their number was estimated by the momentum conservation law for the events with given Q in the collision c.m.s.

The energy of collision is defined by the formula

$$E_{c.m.s.} = \sqrt{S} \approx \sqrt{2\nu_n m_N E_\pi}$$

with m_N the nucleon mass and E_π the energy of incident pion. Such an approach makes it possible to observe the change of the properties of hadron jets, produced on nuclei, with increasing the number of nucleons involved in the interaction what is somewhat similar to an investigation of the properties of hadron jets versus the atomic number of target-nucleus.

The cumulative events were selected using variable $\beta_i = \frac{E_i - P_{i\parallel}}{m_N}$, where E_i and $P_{i\parallel}$ are the energy and longitudinal momentum of secondary particles in the lab.system. According to the established selection criteria, an event assumed to be cumulative if a $\pi^\pm$-meson with $\beta_i \geq 0.6$ or a proton with $\beta_i \geq 1$ was registered in it. However, the hadronization of quarks from multiquark nuclear states can occur so that none of the particles has the value of β_i outside the kinematical limit of pion-nucleon collision whereas the sum of all β_i in a jet, produced in quark hadronization, is larger than 1

$$\beta_o = \sum_i \beta_i > 1.0.$$

As shown [26], the events with cumulative particles incompletely reflect all cumulative processes and their configuration in momentum space. Thus, cumulative interactions were selected according to the above condition: the events were selected in which the value of β_o for a group (jet) of particles, moving backward in the c.m.s. ($\pi^-\nu_n$), was larger than 1. A group of particles satisfying the condition ($\beta_o > 1.0$) was assumed to be a cumulative jet.

Table 1 presents the number of cumulative events thus selected and their fraction of all π^-C interactions. The fraction of cumulative jets with K^o-mesons and Λ^o-hyperons was respectively ~8% and 10% of all cumulative jets.

Table 1

Statistics of events

Type of inter-action	Q	Average number of inter-acting nucleons	Energy $E_{c.m.s.}$ (GeV)	Number of events with given Q and $n_\pm \geq 4$	Fraction of events in % with given Q from all π^-C interactions
1	2	3	4	5	6
Multi-nucleon inter-actions	+1			2032	15
	+2			970	7
	+			395	3
	+4			138	1
	all			3535	28
Events with cumula-tive jets $\beta_o \geq 1.0$	+1	3.0	15.3	1183	8.7
	+2	3.8	17.3	776	5.7
	+3	5.0	20.0	333	2.5
	+4	5.5	21.0	127	0.9
	all			2419	18
Events with cumula-tive jets $\beta_o \geq 1.5$	+1	3.7	17.0	664	4.9
	+2	4.2	18.2	576	4.3
	+3	5.0	20.0	283	2.1
	+4	5.5	21.0	114	0.8

1.2.1. Properties of common characteristics of jets and hadrons in jets

1. Common characteristics of jets

The study of jet particle production in π^-C interactions has been performed using the standard variables: sphericity (S) and thrust (T). Sphericity (S) is defined as follows:

$$S = \frac{3}{2} \min \left(\sum_i P_{\perp i}^2 / \sum_i |\vec{P}_i^*|^2 \right)$$

with $\vec{P}_i^*$ the momenta of secondary particles in the collision c.m.s. and $P_{\perp i}$ the transverse momenta of particles relative to some axis.

The axis, for which $\sum P_{\perp i}^{2}$ has a minimum value, is assumed to be a jet axis. Thrust (T) is found according to the formula:

$$T = max\left(\sum_i |P^*_{\parallel}|_i / \sum_i |\bar{P}^*_i|\right).$$

Here $P^*_{\parallel i}$ is the projection of the momenta of secondary particles on some direction. The jet axis is defined as an axis which maximizes the sum $\sum |P^*_{\parallel}|_i$. These variables are described in detail in paper/27/. It should be noted that variables S and T determine the jet cone opening angle.

Figure 5 shows the dependence of average values of sphericity $\langle S \rangle$ on collision energy $E_{c.m.s.}$ for e^+e^- (∇, o) annihilation. An average value of $\langle S \rangle$ for π^-p interactions at $E_{c.m.s.}$=8.7 GeV is also shown by an arrow. In the same figure are presented average values of $\langle S \rangle$ versus $E_{c.m.s.}$ for the jets of secondary particles collimated towards a primary pion and in an opposite direction in the cumulative (●) and noncumulative (▲) events. As seen from the figure, the value of $\langle S \rangle$ for both jets in cumulative π^-C interactions agrees with the e^+e^- data at equal energies in the c.m.s. For the noncumulative events one can see a disagreement with similar data on e^+e^- interactions for the hadron jets produced in the fragmentation region of target-nucleus. An analogous picture is observed when comparing the values of variable $\langle T \rangle$.

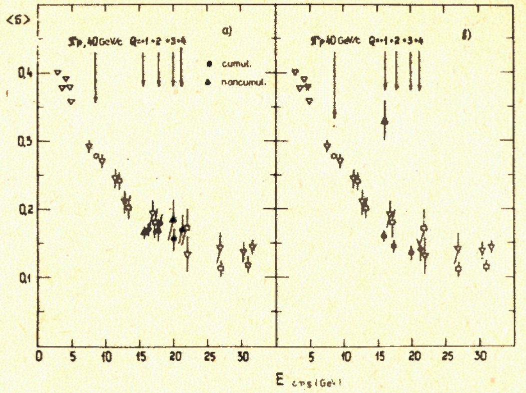

Fig. 5

In order to rule out a possible influence of such nuclear effects as Fermi-motion and pion absorption in the nucleus which can lead to the production of particles and groups of particles with the value of $\beta_{i,0}$ outside the kinematical limit of pion-nucleon collisions, we have selected jets with $\beta_0 \geq 1.5$.

For the cumulative jets thus selected, the dependence of average values of $\langle S \rangle$ on energy $E_{c.m.s.}$ does not differ from that presented in fig.5.

2. Multiplicity of secondary particles

It is known that in various types of hadron-hadron interactions and in e^+e^- annihilation the multiplicity of charged particles is different: e.g., in pp collisions the average values of $\langle n_{\pm} \rangle$ are smaller than in e^+e^- annihilation at the same energies in the c.m.s., and in π^-p and K^-p interactions the values of $\langle n_{\pm} \rangle$ coincide with the e^+e^- data at $\sqrt{s} \leq 12$ GeV. It is of interest to compare the multiplicity $\langle n_{\pm} \rangle$ in e^+e^- annihilation and in cumulative processes.

Figure 6 depicts the average multiplicity of charged particles versus $\sqrt{s}$ in e^+e^- and cumulative π^-C collisions. It is seen that in cumulative processes the value of $\langle n_{\pm} \rangle$ increases with increasing $E_{c.m.s.}$, and, within experimental errors, it coincides with the values of $\langle n_{\pm} \rangle$ for e^+e^- annihilation at equal $E_{c.m.s.}$. However, the analysis has shown that this increase of $\langle n_{\pm} \rangle$ in cumulative processes is greatly due to increasing the number of protons in the final state/21/.

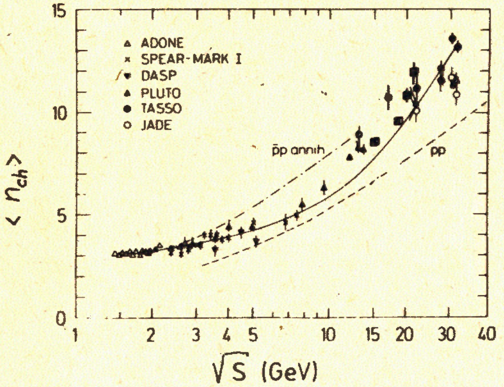

Fig. 6

Table 2 shows the average multiplicities of K^0-mesons and Λ^0-hyperons in π^-p and cumulative π^-C interactions with charge Q = +1,+2. As seen from the Table, the multiplicities of K^0-mesons and Λ^0-hyperons in cumulative interactions are larger than in pion-proton collisions. Nevertheless, in π^-C events the multiplicity of neutral kaons increases proportionally to the average multiplicity of π^0-mesons, $\langle n_{\pi^0} \rangle$ in these events. It is supposed that γ-quanta in the events are mainly produced from the decays of π^0-mesons, therefore $\langle n_{\pi^0} \rangle = \frac{1}{2}\langle n_{\gamma} \rangle$, so that, within the experimental errors, the ratio $\langle n_{K^0} \rangle / \langle n_{\pi^0} \rangle$ is similar for these interactions. Consequently, in cumulative processes no additional sources of strange meson production is observed as compared to neutral pions.

In comparison with the multiplicity of Λ^0-hyperons in pion-nucleon collisions, the multiplicity of Λ^0-hyperons in cumulative events increases approximately in proportion to the number of nucleons involved in the interaction.

Within the experimental errors, the ratio $\langle n_{\Lambda} \rangle / \langle n_{\pi} \rangle$ is similar for π^-p and π^-C interactions.

Table 2

Multiplicities of K^0-mesons and Λ^0-hyperons in π^-p and cumulative π^-C interactions

Type of interaction	π^-p		π^-C	$Q = +1,+2$ 3.3
Type of particles	K^0	Λ^0	K^0	Λ^0
$\langle n_{K,\Lambda}\rangle$	0.23±0.01	0.065±0.006	0.34±0.02	0.16±0.01
$\langle n_{K,\Lambda}\rangle/\langle n_{\pi}\rangle$	0.090±0.006	0.025±0.002	0.098±0.006	0.045±0.004
$\langle n_{K,\Lambda}\rangle/\langle \nu_n\rangle$	0.23±0.01	0.065±0.006	0.102±0.006	0.047±0.004

3. Characteristics of charged particles in jets

Besides the analysis of the collective characteristics of the jets, sphericity and thrust, it is interesting to compare one-particle momentum distributions of secondary particles in the jets for cumulative π^-C and e^+e^- interactions.

Figure 7 presents the behaviour of the invariant production cross sections of π^--mesons and protons from cumulative jets versus variable β_i. As seen, approximating the experimental data by the dependence

$$\rho(\beta_i) = Const\ exp(-\beta_i/\langle\beta_i\rangle),$$

we get $\langle\beta_i\rangle = 0.145 \pm 0.005$ for π^--mesons and $\langle\beta_i\rangle = 0.122 \pm 0.008$ for protons. Within experimental errors, the values of $\langle\beta_i\rangle$ are independent of the number of interacting nucleons of the target-nucleus in the range from 2 up to 5, and they are in good agreement with the universal parameter $\langle X\rangle = 0.14$ obtained previously in experiments on limiting fragmentation by the V.S.Stavinsky group.

A comparative analysis of the ratios of the production cross sections of one charged hadron to those of hadron jets, σ_1/σ_{jet}, for π^-C (Q is from +1 to +4) and π^-p interactions shows that the cross sections of cumulative jets flying forward in the c.m.s.

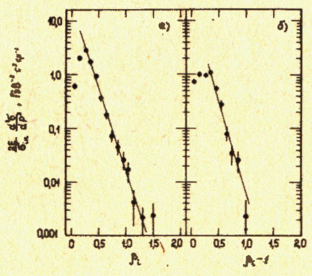

Fig. 7

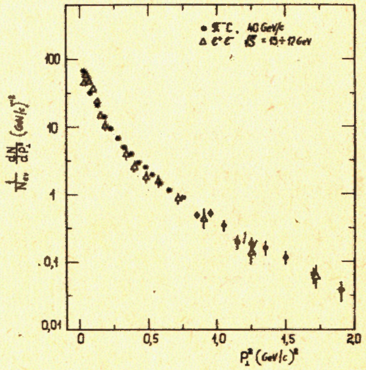

Fig. 8

increase by a factor of ~ 10 in cumulative processes as compared to similar π^-p results.

In fig. 8 is shown the transverse momentum squared distribution of all secondary particles in cumulative interactions with $Q = +1$ relative to the jet axis. The $P_\perp^2$ distributions of particles are similar, within the experimental errors, for the jets produced in the forward and backward hemisphere in the c.m.s. of ($\pi^- \nu_n$) collisions. So figure 8 presents the summed distribution for both hemispheres. The transvers momentum squared distribution of charged particles relative to the jet axis in e^+e^- annihilation for approximately close energies ($\sqrt{S} = 13 \div 17$ GeV) is given in the same figure for comparison. As seen, these distributions are similar for both types of the interactions considered.

Figure 9 illustrates the $x_\parallel = 2P_\parallel/E_{c.s.m.}$ distributions of secondary particles in the forward and backward hemisphere in the c.m.s. of π^-C interactions with $Q = +1$, where $P_\parallel$ is the longitudinal momentum of particles relative to the jet axis. The data are compared with a similar distribution for e^+e^- annihilation at $\sqrt{S} = 7.4$ GeV/27/. The distribution is normalized so that the area under it in the range $|x_\parallel| \geq 0.1$ is the same as in π^-C events.

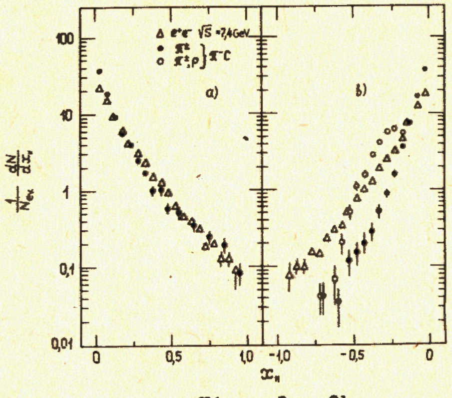

Fig. 9a, 9b

From the figure one can see that in cumulative π^-C collisions the distribution of particles in the jets, collimated towards an incident π^--meson, is in agreement with a similar distribution in e^+e^- interactions. For particles, produced in the fragmentation nuclear region in these events (both for pions and for protons), the $x_\parallel$ distribution relative to the jet axis differs from a similar distribution of charged particles in e^+e^- annihilation.

This difference can be due to variations of initial states of interacting objects which leads to various compositions of secondary particles in the final state and to differences in their phase space distributions (in cumulative π^-C interactions with $Q = +1$ the average number of nucleons, $\langle\nu_n\rangle$, is ~ 3.3 whereas in e^+e^- annihilations at $\sqrt{S} = 7.4$ GeV the mean multiplicity of $p\bar{p}$ pair per event $\langle n_{p\bar{p}}\rangle$ is 0.1).

Therefore it would be more correct to compare identical systems of secondary particles in the final state (in this case meson ones) in their rest frame.

With this aim the events with two identified protons were selected from cumulative π^-C interactions with $Q = +1$. The protons were excluded from the analysis; the energy of the remaining meson system, $\langle M_o \rangle$, was 10 GeV. The value of $\langle M_o \rangle$ was decreased by 6% if the fraction of neutrons in the final state was accounted for.

The $x_R^S = 2P^S/M_o$ and $y_{\shortparallel}^S$ distributions of charged pions, calculated in the rest frame of mesons (M^o), were analyzed. In this case P^S is the total momentum of pions in their rest frame (M_o) and $y_{\shortparallel}^S$ the rapidity determined relative to the jet axis in the same system (the jet axis was reconstructed by variable T).

In such an approach the production of pion jets in the fragmentation region of target-nucleus can be interpreted as a result of the fragmentation of quarks from multiquark states of carbon nucleus.

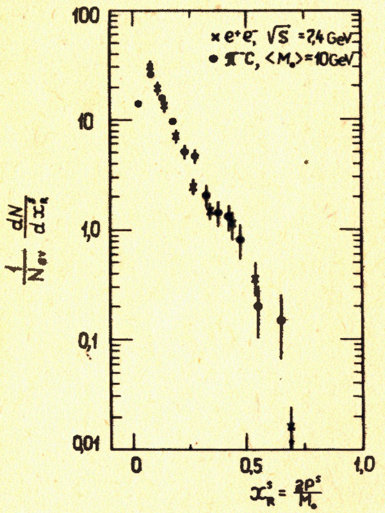

Fig. 10

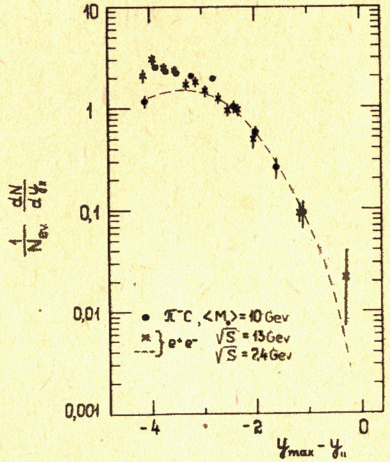

Fig. 11

Figures 10 and 11 compare the dN/dx_R^S and $dN/dy_{\shortparallel}^S$ distributions of charged pions, produced in the nuclear fragmentation region for cumulative π^-C events at $\langle M_o \rangle = 10$ GeV, with the X_R^S and $y_{\shortparallel}^S$ distributions of pions in e^+e^- annihilation for approximately equal energies $\sqrt{S}$. As seen from the figures, these distributions of pions are similar for both types of interaction.

1.2.2. Quark and diquark fragmentation into strange particles

Comparing the processes of quark and diquark fragmentation into neutral K-mesons and Λ^o-hyperons for various types of interaction, we use the scaling function $S/\beta\,(d\sigma/dx_E)$ in terms of which the e^+e^- data are analyzed. Here $x_E = 2E^*/\sqrt{S}$; $\beta = P^*/E^*$; P^* and E^* are the momentum and energy of the considered hadron in the collision c.m.s. According to quark-parton model predictions, for quark fragmentation

this function depends only on variable x_E:

$$\frac{S}{\beta}\frac{d\sigma}{dx_E} \sim F_q(x_E).$$

As taking into account factor S is important only for e^+e^- annihilation, we analyze the function $1/\beta\,(d\sigma/dx_E)$ as in paper /24/.

1. Fragmentation of $\bar{u}(d)$ quarks into strange particles

Figures 12 and 13 present the $\frac{1}{\beta}\frac{d\sigma}{dx_E}$ function versus x_E for neutral K-mesons and Λ^o-hyperons produced in the cumulative processes in the forward hemisphere in the c.m.s. of $\pi^- \nu_n$ collisions. Similar distributions for neutral strange particles in $\pi^- p$ and e^+e^- interactions are given in the same figures /25/.

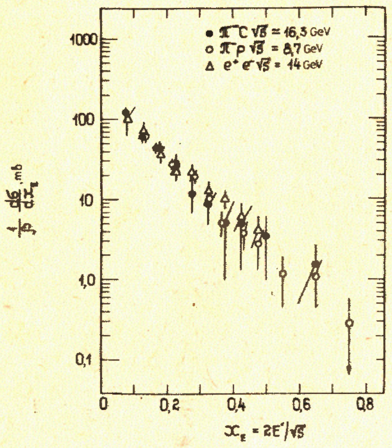

Fig. 12

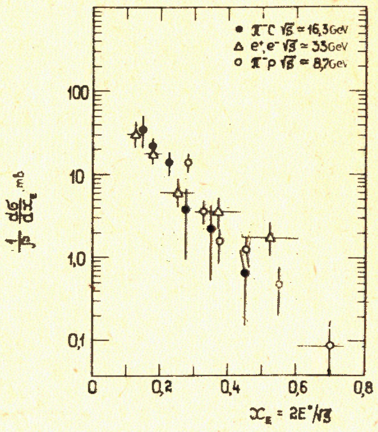

Fig. 13

From the figures one can see that, within the experimental errors, the dependence of the function $1/\beta\,(d\sigma/dx_E)$ on x_E is similar for K^o-mesons and Λ^o-hyperons in cumulative π^-C, $\pi^- p$ and e^+e^- interactions. The $1/\beta\,(d\sigma/dx_E)$ distributions for K^o- and Λ^o-particles can be approximated by the exponential dependence

$$\frac{1}{\beta}\frac{d\sigma}{dx_E} = A\exp(-Bx_E).$$

From figures 12 and 13 it is seen that, within the experimental errors, the slopes of the $1/\beta\,(d\sigma/dx_E)$ distributions determined by parameter B coincide for K^o-mesons and Λ^o-hyperons produced in quark fragmentation (forward hemisphere), in cumulative π^-C, π^-p and e^+e^- collisions /30/.

The average multiplicities of K^o-mesons and Λ^o-hyperons, produced in quark fragmentation in π^-p and cumulative π^-C interactions, are also similar:

$\langle n_K \rangle_{\pi^-C} = 0.072 \pm 0.014$; $\langle n_K \rangle_{\pi^-p} = 0.065 \pm 0.005$ for $0.2 \le x_E \le 0.5$;

$\langle n_\Lambda \rangle_{\pi^-C} = 0.006 \pm 0.003$; $\langle n_\Lambda \rangle_{\pi^-p} = 0.006 \pm 0.001$ for $0.3 \le x_E \le 0.6$.

These values of $\langle n_K \rangle$ and $\langle n_\Lambda \rangle$ are in approximate agreement with the average multiplicity of K°-mesons and Λ°-hyperons produced in e^+e^- collisions due to strange sea quarks /31/ in the same x_E range.

Using tha data obtained, we have made an attempt to evaluate a relative pickup probability of strange $s(\bar{s})$ quarks from the sea in comparison with $u(\bar{u})$ and $d(\bar{d})$ quarks. This probability can be determined by $\lambda_s = \langle n_K \rangle / \langle n_\pi \rangle$. The value of λ_s for cumulative $\pi^- C$ interactions turned out to be $0,18 \pm 0.03$ what, within the experimental errors, agrees with that of λ_s obtained for $\pi^- p$ and e^+e^- collisions /24, 31/. For quark fragmentation a relative pickup probability of diquarks from the sea determined by the relation $\lambda_{qq} = \frac{\langle n_\Lambda \rangle}{\langle n_K \rangle}$ was 0.11 ± 0.06. The same value of λ_{qq} was obtained in $\pi^- p$ interactions (0.14 ± 0.03) /24/ and e^+e^- annihilation (~ 0.08) /29/.

2. Diquark fragmentation into strange particles

As shown in the previous paragraph, in order to compare correctly the properties of hadron jets in various types of interactions, it is necessary to select identical systems of secondary particles in the final state. This is the reason why for comparison of the properties of K°-mesons and Λ°-hyperons, produced in the target-nucleus fragmentation region in cumulative processes, with the $\pi^- p$ and e^+e^- data, we have selected a system of secondary particles consisting of mesons and a baryon. Then the production of Λ°-hyperons and K°-mesons in the backward hemisphere in the rest frame of the selected subsystem can be considered as a result of the fragmentation of uu, ud or dd diquarks from multiquark states of carbon nucleus and other baryons as spectators. Cumulative $\pi^- C$ collisions with $Q=+1$ and one identified proton, with $Q=+2$ and two protons were selected for this comparison. These protons were not excluded from the analysis. The energy of the remaining subsystem of secondary particles, $\langle M_0 \rangle$, was 12.3 GeV.

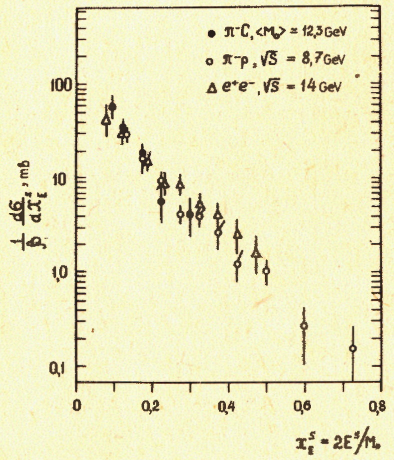

Fig. 14

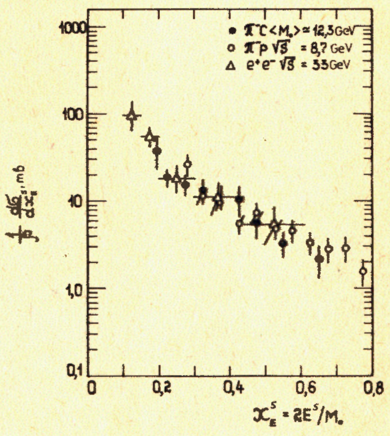

Fig. 15

Figures 14 and 15 show the $\frac{1}{\beta}\frac{d\sigma}{dx_E^s}$ function versus x_E^s for K°-mesons and Λ°-hyperons produced in the target-nucleus fragmentation

region for cumulative $\pi^- C$ interactions with $Q=+1,+2$. Here $x_E^s = 2E^s/M_0$ and E^s is the energy of particles in the rest frame of subsystem M_0. In the figures are also presented the $1/\beta(d\sigma/dx_E)$ distributions for neutral strange particles from e^+e^- and $\pi^- p$ collisions in the backward hemisphere in the c.m.s. As seen from the figures, the $1/\beta(d\sigma/dx_E^s)$ distributions for K°-mesons and Λ°-hyperons agree, within the experimental errors, in the considered x_E^s range for these different processes. The slopes B of the $1/\beta(d\sigma/dx_E^s)$ distribution for neutral strange particles produced in the backward hemisphere in the rest frame of subsystem M_0 can be obtained by approximating these distributions by the dependence mentioned above. From figures 14 and 15 it is seen that the value of parameter B for K°- and Λ°-particles in cumulative events are consistent, within the errors, with the data. The value of slope B is also similar for K°-mesons from cumulative events and e^+e^- annihilation. As for Λ°-hyperons produced from diquark fragmentation in $\pi^- p$ and cumulative $\pi^- C$ interactions, the slope B is smaller than in e^+e^- annihilation.

The results obtained mean that diquark fragmentation into neutral kaons and Λ°-hyperons from multiquark states in light nuclei occurs in the same manner as diquark fragmentation into the same particles for soft hadron interactions.

Conclusion

Summarizing all the foregoing, the following conclusions can be drawn:

- the established regularities, following from the experimental data obtained in limiting fragmentation experiments at the synchrophasotron, show evidence for the existence in nuclei multiquark states which strongly differ from nucleons in their structure. These regularities have been in part confirmed in CERN (NA-4 and EMS) and SLAC experiments on deep-inelastic muon and electron scattering on nuclei;

- results of studying correlation phenomena and hadron jet production in cumulative hadron-nucleus processes indicate that the fragmentation of multiquark states in light nuclei is similar to that of quarks and diquarks in "soft" and "hard" hadron collisions;

- in hadron interactions with light nuclei the fragmentation of quarks into hadron jets occurs mainly outside the nucleus.

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Кумулятивный эффект и процессы множественного образования частиц

Дается обзор экспериментальных результатов изучения коррекционных явлений и свойств струй адронов, образованных в кумулятивных адрон-ядерных взаимодействиях при импульсах 10 и 40 ГэВ/с. Исследования выполнены на снимках с 2-метровой пропановой пузырьковой камеры Лаборатории высоких энергий ОИЯИ.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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