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Quark-Parton Picture of the Cumulative Production

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I. INTRODUCTION

The unusual nuclear physics associated today with the quark structure of the constituent nucleons started in 1957, when at Dubna in the 660 MeV proton beam G.A.Leksin [1] discovered the proton yield to the backward hemisphere from a nucleus and the group of M.G.Meshcherjakov [2]observed an unusually large deuteron yield from light nuclei. For explanation of this phenomena D.I.Blokhintsev [3] suggested the same year the hypothesis of the fluctuation of the density of nuclear matter, i.e. the creation and disintegration of a short lived few-nucleon correlations ("fluctons"). "In the considered case - he wrote, the transfer momenta are so large that the whole process comes due to an extremely high harmonics of the deuteron wave function, i.e. due to such states where both nucleons are close to each other and can not be considered as independent in collision of them with a third nucleon".

A new period in the study of unusual nuclear phenomena begins by the prediction by A.M.Baldin [4] and experimental discovery by V.S.Stavinsky group [5] of the cumulative particle production, i.e. the inclusive production of secondary particles off nuclei beyond the kinematical region allowed by scattering with one nonmoving nucleon of the nucleus. Experimental and theoretical investigation of this phenomenon, its astonishing properties and also elastic and deep inelastic lepton nuclear scattering lead now to a new trend: the relativistic nuclear physics at the edge of high energy and nuclear physics.

Most of the physicists investigating the cumulative production seem to be convinced now that the classical mechanisms of the Fermi-motion and the multiple scattering are unable to explain the features of the phenomenon. As to the flucton idea, there is a spectrum of approaches in literature which differ by answers to the following questions:

i) Does the flucton exist in the nucleus before the collision or is it created by the incident particle?

ii) What is the flucton? A quasiresonance formation or a coherent (from the projectile point of view) group of nuclei (a coherent tube)?

iii) What is the mechanism of cumulative production? The fragmentation of a flucton or the hard scattering of partons from the incident particle and flucton?

The present paper is an attempt to answer these questions by a qualitative comparison of features of different models with experimental data.. In this work we confine ourselves mostly to the cumulative meson production, where the situation seems more unambiguous than for production of heavy fragments. As a result, we can conclude that the flucton, by all means is a sort of the quasiresonance formation in the nucleus which exists without any connection with the incident particle and the cumulative production in the investigated now region is mostly the result of a sort of a Regge type dissociation of the flucton.

2. KINEMATICS AND MAIN FEATURES

The invariant cross section of inclusive process $B+A \to C+X$ (Fig.1) $\epsilon \frac{d\sigma}{d\vec{p}}$ depends on three invariant variables

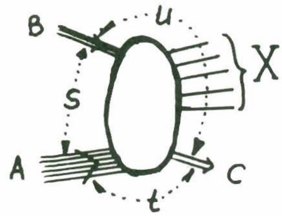


Fig.1

$$s = 2p_A p_B = 2mE$$

$$t = 2p_A p_C = 2m\epsilon \qquad (1)$$

$$u = 2p_B p_C \approx 2E(\epsilon - p\cos\theta),$$

where p_A, p_B, p_C are the 4-momenta of a nucleon in a nucleus A and of particles B and C; E, P, ϵ, p are the energy and momentum of the beam and secondary particle C and θ is the scattering angle in the Lab.frame. We will use also the dimensionless variables

$$x = \frac{u}{s} \simeq \frac{\epsilon - p\cos\theta}{m}, \qquad y = \frac{t}{s} = \frac{\epsilon}{E}$$

and variable (2)

$$\tau^2 = \frac{ut}{s} \simeq 4p^2 \sin^2\frac{\theta}{2}$$

The order of cumulativity Q is defined as a minimal mass of the target for a given s,u and t (in units of the nucleon mass). If $(M_X)_{min} = Qm + \Delta m$ then

$$Q = \frac{u + (\Delta m)^2}{s - t - 2m\Delta m} \simeq x \qquad (3)$$

So, the cumulative production is defined as the region of

$$Q > 1$$

At the present time an abundant and diverse experimental material is obtained and collected in a number review papers [6-10]. The experiments have been performed at different energies up to 400 GeV for different beams (p, π, γ, e, μ) and nuclear targets and different secondary particles (p, π, K, d, t, e, μ etc.). These are features of the cross section:

a) The initial energy dependence [7,8]. It was found that beyond some energy E_0 the cross sections are almost constants. Only a slow variation was seen up to 400 GeV. The boundary E_0, however, depends on the type of beam B and target A. It was found that $E_{0\gamma} < E_{0\,\mathrm{hadr.}}$, and $E_{0\,\mathrm{hadr.}}$ shifts to a higher value (see Fig.2 where the cumulative proton cross sections are presented) with increasing the atomic number A ($\sim A^{1/3} E_{0\gamma}$).

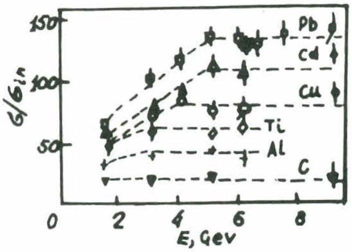


Fig.2

b) Angular and momentum dependence. One of the most remarkable features of cumulative production is a universal form of the distribution over the variable x almost the same for different beams, targets and secondaries. Approximately for $\theta \simeq 180^0$ it has the exponential form (Fig.3)

$$\epsilon \frac{d\sigma}{d\vec{p}} \sim \exp\{-\frac{x}{\langle x\rangle}\} \qquad (4)$$

where the average $\langle x\rangle \simeq 0.16$. Fig.4 illustrates this fact. Especially, one should stress approximately the same slope for deep inelastic cumulative scattering $\mu + {}^{12}C \to \mu + X$ according to preliminary communication of the NA-4 experimental group. It is necessary to note, however, that expression (4) does not include all the angular dependence. There is some decrease [10,12] of the cross section when the angle decreases at x fixed (Fig.5).

c) A-dependence. A-dependence is one of the most specific features of the cumulative production. For pointlike particles (γ, e, μ) it is known that [7] $\epsilon \frac{d\sigma}{d\vec{p}} \sim A$. However, for the pion and nucleon production a very complicated A-dependence has recently been observed [10] (Fig.6).

$$\epsilon \frac{d\sigma}{d\vec{p}} \sim \begin{cases} A & \text{for heavy nuclei} \\ A^{n>1} & \text{for light nuclei} \end{cases} \qquad (5)$$

A stronger A-dependence was observed for heavy fragments [7].

$$\epsilon \frac{d\sigma}{d\vec{p}} \sim \begin{cases} A^{5/3} \text{ for d} \\ A^{2} \text{ for t} \end{cases} \text{for proton beam} \quad \begin{cases} A^{4/3} \\ A^{5/3} \end{cases} \text{for pion beam} \qquad (6)$$

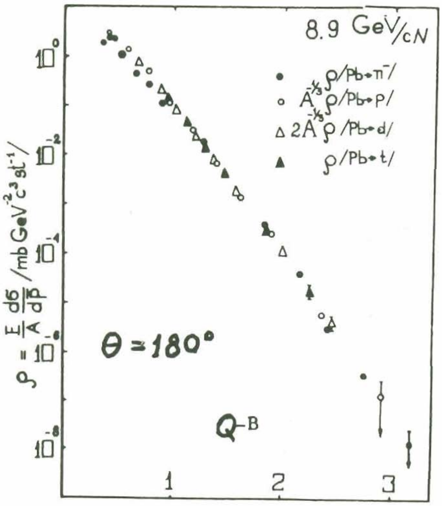


Fig.3

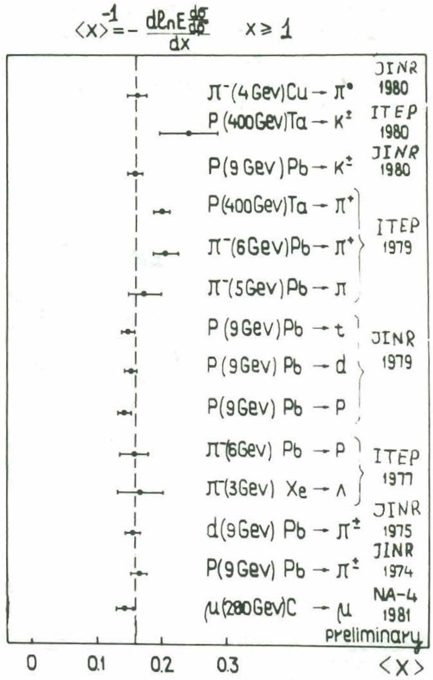


Fig.4

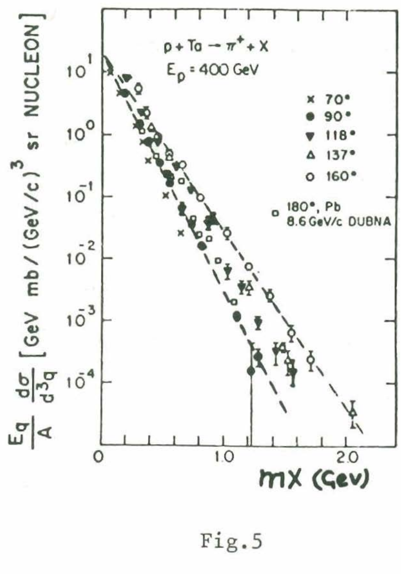


Fig.5

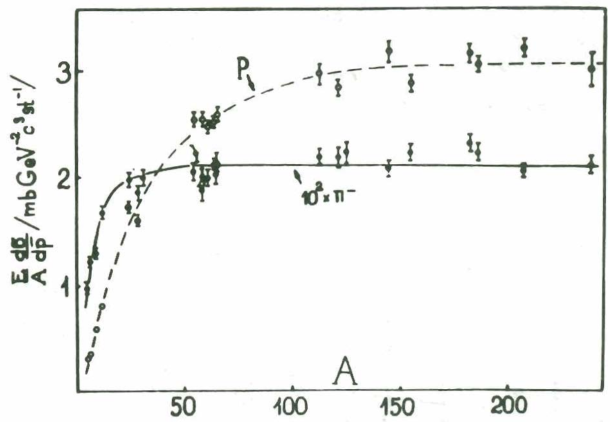
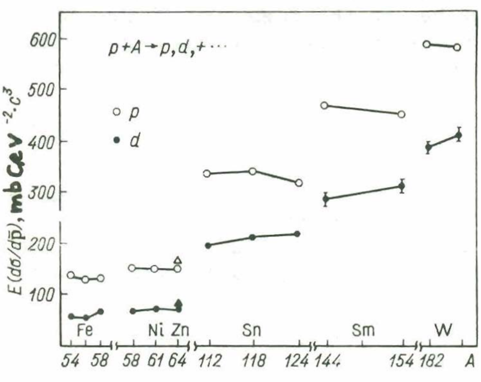


Fig.6

An interesting phenomenon was observed [7] for the cumulative p and π^+. The cross section turns out to depend on the number of protons Z rather than on the number A (Fig.7,8).



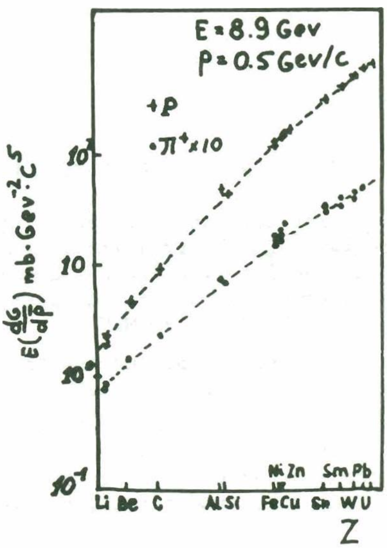


Fig.7

d) Relative yield of different particles. Most of the experiments show that the ratio of π^-/π^+ yield in the cumulative region is close to one [7] (Fig.9) and weakly grows when the pion momentum increases. Also the ratio K^+/π^+ is close to one for equal cumulative indices Q [10] (Fig.10). However, the ratio of K^+/K^- is large [12,13] ($\simeq 30 \div 100$ for $x \approx 1$) (Fig.11), larger than for NN process.

The ratio of the heavy fragments to the pion yield is well illustrated by Fig.3.

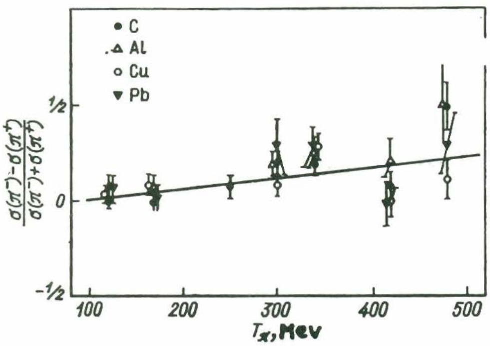


Fig.9

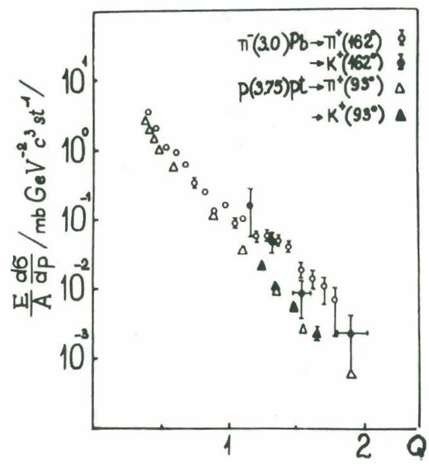


Fig.10

3. INADEQUACY OF CLASSICAL EXPLANATION

A. The Fermi motion. It is interesting to recall that phenomena outside the kinematical region were observed for a long time before the discovery of the cumulative particle production. The first "handmade" pions from an accelerator of the proton beam were observed in 1948 at the energy of the proton beam $\simeq 150$ MeV, though the production threshold is 290 MeV.

Although the antiproton production threshold is 6.6 GeV, however, experimentally it has been observed at 3.9 GeV.

The conventional explanation of this anomaly was the Fermi motion of nucleons the average momentum of which is $p_F \simeq 300$ MeV/c. It is not difficult to calculate that for the antinucleon production the nucleon in a nucleus could have the momentum 0.6 GeV/c. (The same effect, however, gives the coherent scattering on a target of mass 3m).

For understanding the cumulative production this mechanism seems not to be sufficient for the following reasons [8]:

i) It is difficult to explain quantitatively magnitude of the cross section beyond the momentum 300 MeV/c [14,15]. At the momenta $p \approx 1$ GeV/c the difference is 5 or 6 orders of magnitude.

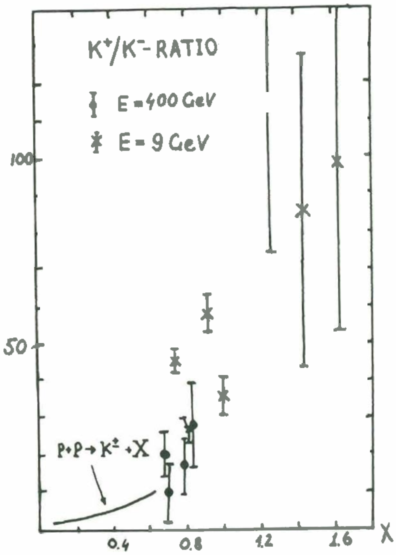


Fig.11

ii) Qualitatively, it is difficult to understand the similarity of spectra from the deuterium and heavy nuclei which have different p_F.

iii) Also, it is difficult to understand the observed strong dependence on A for heavy nuclei.

These objections are valid also for all models in which the momenta of the interacting nucleon is balanced by all A-1 nucleons of the nucleus [16-19] . The wave function of a nucleon in such models is determined by an average field made by other nucleons and so it looks as a modification of the Fermi motion.

B. Manifold scattering [20] . This mechanism is also unable to explain the cumulative particle production [15]. The maximal momentum after an n-fold scattering is reached when the scattering angle in each act equals θ/n . Its value in this case is

$$p_n \simeq \frac{P(\cos\frac{\theta}{n})^n}{1-(\cos\frac{\theta}{n})^{2n}} \qquad (7)$$

From this expression it follows that for the deuteron it is impossible to have a nucleon flying strictly in the backward direction. It is not difficult to estimate the maximal number of scatterings for a heavy nucleus. It is seen from Fig.12 that

$$R = r_0 + \frac{r_0}{\sin\theta/2n} \simeq r_0 A^{1/3}$$

or

$$n_{max} = \frac{\theta}{2 \sin^{-1}[A^{1/3}-1]^{-1}}$$

For instance, for ^{28}Al target, $\theta = 180^{\circ}$, and $E = 10$ GeV, $n_{max} = 3$. So, the maximal momentum $p_{max} = 9$ GeV/c/2^4 = 0.56 GeV/c. Experimentally, the nucleons with momenta $p \simeq 1$ GeV/c have been seen.

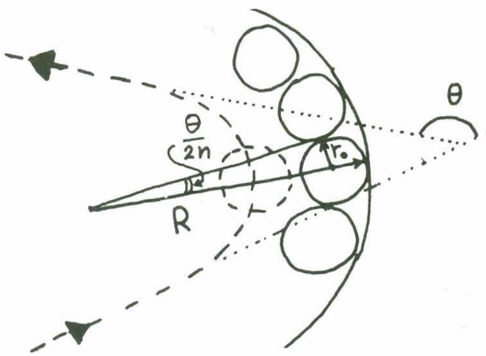


Fig.12

So, we can conclude that neither Fermi motion nor multiple scattering can play a main role in the cumulative particle production. Nevertheless, they can be important as corrections, especially, in the region of small momenta below 300 MeV/c. Today it seems commonly accepted that the main role there plays the scattering with a fluctuation of the density of nuclear matter when several nucleons are gathering in a small volume (compare to the average volume per nucleon) at a distance r_c of an order of the nucleon dimension itself ($r_c \simeq$ 0.75 fm).

These phenomena, of course, can be described in a different language: for instance, as a few nucleon momentum correlation [8], where a large momentum of one nucleon is balanced by momenta of several others, or, probably even as a high momentum component of the one-nucleon wave function. However, the most productive, in our opinion, is the language of distance. (Authors of [8] also turn to the distance language when estimate the many-nucleon correlation).

There is a spectrum of different opinions, however, concerning the questions: What is the flucton? Does it exist before collision or is made by a projectile? What is the mechanism of cumulative particle production?

4. DOES THE FLUCTON EXIST BEFORE COLLISION?

Most of the works on cumulative production accept the Blokhintsev point of view [3] that fluctons as a random fluctuation of nuclear matter have to exist in the nucleus in no connection with the incident particle. Afterwards, however, there have appeared trends which consider the possibility of creation of such a dense state by the incident particle due to the compression of nuclear matter [21] or by the production of a fairball in the first act of interaction and absorption of nuclear matter in the course of its propagation [22-24] . (The difference between these models is unessential for us now).

Such models succeed in explaining many qualitative and quantitative features of the cross section (momentum and energy dependence, A-dependence, etc). Other features seem to be difficult to explain (e.g. K^+/K^- ratio). However, the most principal from our point of view is the difficulty in the explanation of cumulative leptons in deep inelastic scattering, by the nucleus, i.e. the process $\mu(e) + A \to \mu(e) + X$ in the region $x = -q^2/2p_A q > 1$ (where q is the lepton 4-momentum transfer). Since the lepton cannot gather the nuclear matter and it does not care about processes in the nucleus after its scattering with a quark of a nucleon such models can explain neither a nonzero structure function beyond $x > 1$ observed experimentally for d , ^3He , ^4He in SLAC and ^{12}C in NA-4 experiment, especially, nor its similarity to the cumulative hadron spectrum. (See Fig.4). The question about the gathering mechanism as a correction in hadron processes has to be solved by quantitative comparison of hadron and lepton processes.

5. WHAT IS THE FLUCTON?

There exist two points of view [6,25] :

A) The flucton is a coherent (for the incident particle) formation of nucleons [26,27]. The coherence is states by emission and absorption of virtual gluons moving with the velocity of light. So for the incident particle those nucleons can be coherents which are in a volume of radius $r_c \simeq 0.75$ fm. In the nucleus rest frame this volume is stretched by a γ-factor in the longitudinal direction, and when the initial energy is large enough ($\gamma > R/r_c$) , the coherence volume cuts out of the nucleus a "coherent tube" of the cross section area $\sigma \simeq \pi r_c^2$.

It is not difficult to estimate the probability of such a formation. Let us assume that the nuclear wave function can be approximated by the product of A identical one nucleon functions. The probability of one nucleon to get into the tube with an impact parameter b is

$$\sigma \cdot T(b) = \sigma \cdot \int_{-\infty}^{\infty} \rho(b,z)\, dz$$

where $\rho(b,z)$ is the relative nuclear density normalized as $\int d^3r\, \rho(r) = 1$ (The Woods-Saxon density $\rho = \rho_0[1+\exp(R-r)/d]^{-1}$ where $R = 1.1A^{1/3}$ and $d = 0.54$ fm can be used). The probability to find nucleons in the tube for a nucleus made of A nucleons is

$$P(k,b,A) = \binom{A}{k} (\sigma\, T(b))^k (1-\sigma T(b))^{A-k} \tag{8}$$

So, the total probability of the k-nucleon fluctuation is

$$P(k,A) \simeq \frac{1}{\sigma} \int d^2b\, P(k,b,A) \tag{9}$$

In the approximation of constant density (heavy nucleus) $\rho = \frac{1}{V}\theta(R-r)$ the cross section (9) has the form

$$P(k,A) \simeq \binom{A}{k} \frac{2R^2}{(k+1)\, r_c^2} \left[\frac{3}{2}\left(\frac{r_c}{R}\right)^2\right]^k \sim A^{2/3+k/3} \tag{10}$$

B) The flucton is a quasiresonance formation with a definite energy and width [3,8,15], i.e. the coherence volume is a sphere of a volume V_c and radius r_c in the rest frame of the nucleus. The total probability of such a fluctuation of k nucleons is

$$P(k,A) = \frac{1}{V_c} \int d^3r \binom{A}{k} (V_c\, \rho(r))^k (1-V_c \rho(r))^{A-k} \tag{11}$$

or in the approximation of constant density

$$P(k,A) = \binom{A}{k} \left(\frac{V_c}{V}\right)^{k-1} \left(1-\frac{V_c}{V}\right)^{A-k} \sim A \tag{12}$$

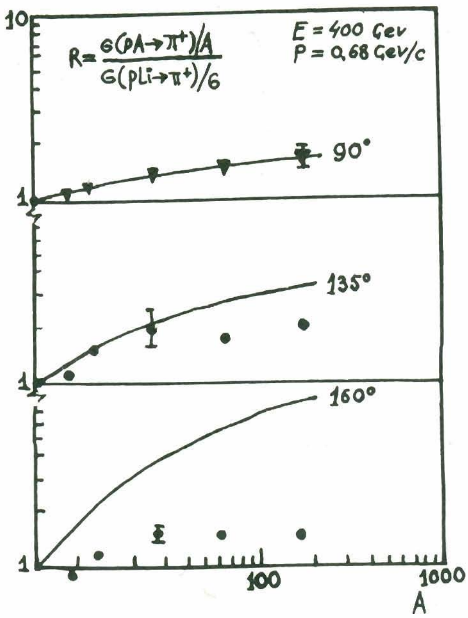


Fig.13

These two hypotheses give the essentially different A-dependence of the cumulative production cross section and can thus be easily discriminated experimentally. As we have seen in Sect.3 for heavy nuclei $d\sigma/A \sim$ const (Fig.7) which is an argument in favour of the flucton B-type. Fig.13 demonstrates also the comparison of the prediction for $R=6\sigma(A\to\pi^+)/A\sigma(Li\to\pi^+)$ of the Coherent Tube Model [27] (the flucton A) in comparison with experimental data of the ITEP-Pensylvania group [12] .

6. WHAT IS THE MECHANISM? FRAGMENTATION?

The most popular current hypothesis of the cumulative particle production is the mechanism of a flucton fragmentation [6,8,15,22,27] . The corresponding diagram is shown in Fig.14, from which it is seen that the cross section of the inclusive meson C production with the fractional momentum $x = \frac{u}{s} \simeq \frac{p_c}{p_{max}}$ (in the rest frame of B) and transverse momentum p_T is proportional to the probability $P(k,A)$,to diquark stripping cross section, and to a number of quarks q in the flucton A_k

with the fractional momentum x and the transverse momentum p_T [27].

$$\epsilon \frac{d\sigma}{d\vec{p}} \sim \sum_{k=1}^{A} P(k,A)\, q_k(x) f(p_T) \qquad (12)$$

In fact, this expression is the quark distribution in nucleus A. It can be extracted either from deep inelastic scattering or estimated in theoretical models.

Concerning the later possibility one can state that since the binding energy of quarks in the nucleon is much greater than the binding energy of nucleons in a nucleus, only one of nucleons of a flucton which takes part in a large transferred momentum process (t >> 1 GeV^2/c), has to be considered as made of (almost) pointlike partons. Other nucleons are passive spectators with frozen quark - gluon degrees of freedom. So, they can be considered as a pointlike constituents.

The fractional momentum distribution in such a flucton can be found as a convolution of the quark-gluon distribution in a nucleon (known from deep inelastic scattering) and the nucleon distribution in a flucton. The former, by all means, cannot be found from a nonrelativistic wave function. However, due to small binding energy, it can be estimated as a fraction of the phase space volume for one pointlike massless nucleon. (The defreezing of the quark-gluon degrees of freedom, e.g., the excitation of the Δ-resonance with a subsequent decay into πN can lead only to the decrease of the fractional phase space per one nucleon).

So, let α be a fractional momentum of one nucleon, then the distribution function is

$$N_k(\alpha) = \frac{k\,\Phi(\alpha)}{\int \Phi(\alpha)\, d\alpha}$$

where

$$\Phi(\alpha)\, d\alpha = \int_1 \dots \int_{k-1} \prod_1^k \frac{dp_j}{p_j}\, \delta(p - p_k - \sum_1^{k-1} p_j)$$

and $p_k = \alpha p$. After integration one obtains

$$N_k = k(2k-1)(2k-2)\,\alpha(1-\alpha)^{2k-3}. \qquad (13)$$

Approximating now the quark and gluon distributions in nucleon as

$$q_N(\alpha) = C_q\, \alpha^a (1-\alpha)^b \qquad (14)$$

(the values of a,b and σ_q for proton are given in Table 1) and making convolution with the nucleon distribution (13)

$$\tilde{q}_k(\alpha) = \int_\alpha^1 q_N(\alpha')\, N_k\left(\frac{\alpha}{\alpha'}\right) \frac{d\alpha'}{\alpha'}$$

one can obtain in terms of $x = \alpha/k$, a fractional momentum per nucleon,

$$\tilde{q}_k(x) = q_N\left(\frac{x}{k}\right)\left(1-\frac{x}{k}\right)^{2k-2} \frac{2k!\,b!}{2\cdot(2k+b-2)!}\, F\left(a+b, 2k+b-1, 1-\frac{x}{k}\right) \simeq$$

$$\simeq C_q \frac{(2k)!\,b!}{2\cdot(2k+b-2)!}\left(1-\frac{x}{k}\right)^{2k+b-2} \qquad (15)$$

Table 1. The Distribution Functions $q_N(\alpha) = C_q\, \alpha^a (1-\alpha)^b$

	a	b	c
$u(\alpha)$	-0.5	3	2.25
$d(\alpha)$	-0.5	4	1.23
$s(\alpha) = \bar{s} = \bar{u} = \bar{d}$	-1	7	0.25
$g(\alpha)$	-1	5	3.0

So, for a nucleus with the atomic weight A and charge Z an average flucton contains kZ/A protons and $k(A-Z)/A$ neutrons, and the distribution functions of u- and d-quarks are

$$u_k(x) = \frac{Z}{A}\tilde{u}_k(x) + \frac{A-Z}{A}\tilde{d}_k(x)$$
$$d_k(x) = \frac{Z}{A}d_k(x) + \frac{A-Z}{A}\tilde{u}_k(x) \qquad (16)$$

Now, let us estimate the behaviour of the cross section (12). For this aim we approximate $\binom{A}{k} \simeq k^{-1/2}\exp\{k\ln(Ae/k)\}$

$$\tilde{q}(x) \simeq \psi(x,k)\exp\{2k\ln(1-x/k)\}, \quad \text{where} \quad \psi(x,k)$$

is a smooth function of x and k and for summation over k use the saddle point method which imediately gives

$$\epsilon\frac{d\sigma}{d\vec{p}} \sim \exp\{-x\frac{(\delta+1)(2-\delta)}{\delta}\}\cdot\phi(x,\delta)f(p_T) \qquad (17)$$

where ϕ is a smooth function and δ is connected with the saddle point position $k_{s.p.} \equiv \bar{k} = (1+\delta)x$ and is determined by the equation

$$\frac{2}{\delta} = \ln\left[\frac{x}{(r_c/r_0)^3}\frac{(\delta+1)^3}{\delta\, 2}\right]$$

The solution of the equation for $r_c = 0.75$, $r_0 = 1.2$ fm and also the value $\langle x\rangle = \delta[(1+\delta)(2-\delta)]^{-1}$ are presented in Fig.15. It is seen that in the region $x \simeq 2\div3$ $\langle x\rangle$ is close to "over the world averaged" $\langle x\rangle = 0.16 \pm 0.01$. This slope is universal for all particles, all the distinction is in the function $\phi(x,\delta)$.

The defreezing of quark-gluon degrees of freedom of the passive nucleons decreases the values of $\langle x\rangle$. In particular, the total defreezing i.e. the so-called passive quark counting rule [28],

$$\tilde{q}_k \sim (1-\frac{x}{k})^{6k+b-2}$$

leads to about 2 times smaller value of $\langle x\rangle$ ($\simeq 0.085$).

It is interesting to note that the ratio $\tilde{d}_k/\tilde{u}_k$ is rather small according to (14) and Table 1 ($\simeq 0.36\,(2\bar{k}+2)^{-1}4(1-x/\bar{k}) \simeq 0.1$ for $x \simeq 1\div2$). This fact can explain the isotopic effect (See Fig.8) for cumulative π^+ and p and predicts also an isotonic (independence of A for equal A−Z) effect for production of π^- and neutrons.

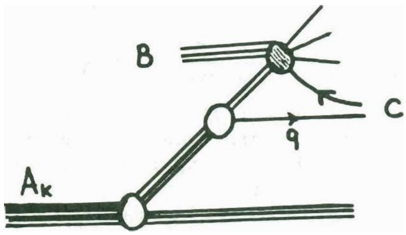
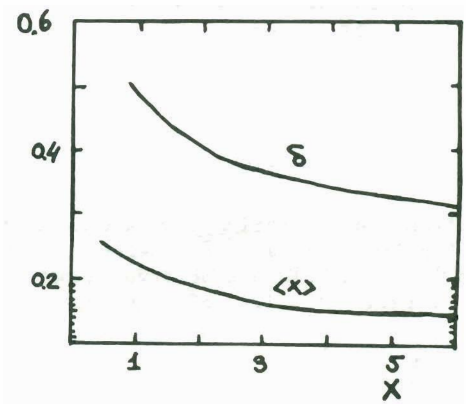


Fig.14



In spite of the success of the fragmentation model there are some questions difficult to answer. The first of them is the production of particles which have no nucleon valence quarks (e.g. K^- or $\bar{p}$). To regard such a particle as a product of fragmentation, it should have at least one quark (antiquark) from the sea of a flucton, which is scarcer than the sea of a nucleon (see (15) and Table I). For the ratio of K^+/K^- , for instance, it is not difficult to obtain

$$\frac{K^+}{K^-} = \frac{u_{\bar{k}}(x)}{2s_{\bar{k}}(x)} = \frac{2.25\cdot 3}{(2\bar{k}+1)}\sqrt{\frac{\bar{k}}{x}}\Big/ 0{,}25\frac{\bar{k}}{x}\frac{(2\bar{k})!\,7!}{(2\bar{k}+5)!}(1-\frac{x}{\bar{k}})^4$$

which is $\simeq 600$ for $x \approx 1$ ($\delta \simeq 0.5$, $\bar{k} \simeq 1.5$) that is ten times as large as its experimental value [12,13] (Fig.11). (This remark, however, does not concern those models which use for the cumulative K^- the experimental yield of K^- on the hydrogen target. Such models strictly speaking cannot be considered as fragmentational since, as is well known [29] the hard scattering mechanism is dominating here.

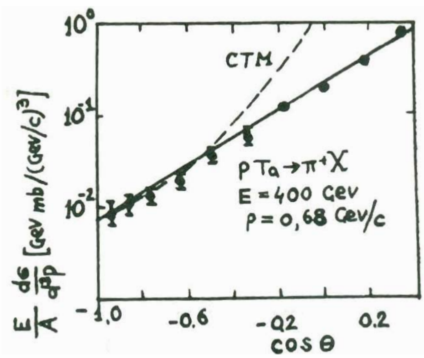


Fig.16

The second difficulty comes from the separation of x- and p_T dependence in (12),(17). It leads to a distortion of the linear $\cos\theta$ dependence of $\log(\epsilon\, d\sigma/d\vec{p})$ (especially, in the region of $\theta \simeq 90°$) which is not observed experimentally. Fig.16 presents the comparison with experiment [12] of θ-dependence of the model [21] with the distribution

$$f(p_T) = \frac{1}{1.45}(\exp(-10\,p_T^2) + 0.45\exp(-2.7\,p_T^2))$$

The third difficulty is the inability to explain an abnormally large polarization of cumulative Λ-particles and protons [30,31] because in the rest frame of C-particle momenta of both its constituents are collinear and there is no normal to a plane.

7. OR PARTON HARD SCATTERING?

One can prove [32] in QCD that the hard parton scattering subprocess is dominating for inclusive production (irrelevant to the beam or target type) in the region when

$$s,u,t >> m^2_{hadr.}$$

and especially (18)

$$\tau^2 = \frac{ut}{s} \simeq 4p^2 \sin^2\frac{\theta}{2} \gg m^2_{hadr.}$$

The second condition in the region of $\theta < 90^\circ$ means really $p_T^2 \gg m^2_{hadr}$. However, in the region $\theta > 90^\circ$ the condition (18) is connected with high $4p^2$ rather than with high p_T^2. This was an argument in favour of the hard scattering mechanism for the cumulative production process [26,18].

The cross section of such a process, as is well known [29], has the form (Fig.17)

$$\epsilon\frac{d\sigma}{d\vec{p}} = \frac{1}{\pi}\iiint d\alpha\, d\beta\, d\gamma \Big(\sum_{k=1}^{A} P(A,k)\, q_k(\alpha)\Big) q_B(\beta) \frac{d\sigma}{dt'} \frac{1}{\gamma} D_C(\gamma)\delta\Big(\gamma - \frac{y}{\beta} - \frac{x}{\alpha}\Big) \quad (19)$$

where $q_k(\alpha)$ and $q_B(\beta)$ are the numbers of partons in the flucton A_k and particle B with the fractional momenta $0 < \alpha < k$ and $0 < \beta < 1$, D_C is the fragmentation function of a scattered parton with the fractional momentum γ and $d\sigma/dt'(s',t'/s')$ is the differential cross section of parton scattering ($s' = \alpha\beta s$, $t' = \alpha t/\gamma$, $u' = \alpha u/\gamma$). These cross sections for quark-gluon scattering have to be calculated from the perturbative QCD [29]. For simplicity, however, we will use its phenomenological form which is [29] for the large s'/t'

$$\frac{d\sigma}{dt'} = \frac{\sigma_0 \gamma^n}{\tau^n}\Big(\frac{s'}{t'}\Big)^{2j-2} \quad (20)$$

where j is an exchanged spin in t-channel the number $n = 8$ $\sigma_0 = 2300$ mb $(GeV/c)^6$ as is known from the high p_T process. (This power effectively takes into account the breaking of scaling, running $\alpha_s(\tau^2)$ in the QCD, and also the Fermi motion of partons).

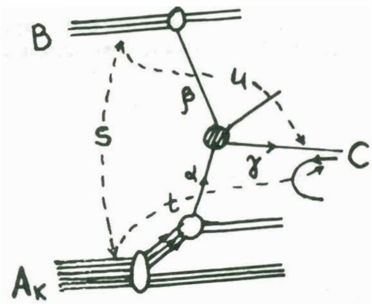


Fig.17

Substitution of (20) into (19) leads, as is well known, to the form

$$\epsilon \frac{d\sigma}{d\vec{p}} = \tau^{-8} I(x,y) \tag{21}$$

In the limit $y \to 0$ the behaviour of I is determined by $\beta q_B(\beta)$ when $\beta \to 0$. So, the valence quarks do not work and only the SU_3 symmetric sea of quark and antiquarks does contribute. So, the form of x-spectrum of particles C is universal and because of $\tau \simeq xm/\sin\theta/2$

$$(\sin\frac{\theta}{2})^{-8} \epsilon \frac{d\sigma}{d\vec{p}} \simeq x^{-8} I(x, y \simeq 0) \tag{22}$$

The experimental data [12] seem to confirm this form (Fig.18).

Integration over α, β, γ and summation over k Sect.6 gives in the limit $y \ll 1$, $(1-x/\bar{k}) \ll 1$

$$I \simeq \phi(x,\delta) e^{-\frac{x}{\langle x \rangle}} \times \begin{cases} \dfrac{\ln\left[\dfrac{1-x/\bar{k}}{13.36\, y}\right] - \dfrac{4\bar{k}+5}{(2\bar{k}+2)(2\bar{k}+3)}}{(2\bar{k}+2)(2\bar{k}+3)} & j=1 \\[2ex] \dfrac{1-x/\bar{k}}{(2\bar{k}+3)(2\bar{k}+4)} & j=1/2 \\[2ex] \dfrac{(1-x/\bar{k})^2}{2(2\bar{k}+4)(2\bar{k}+5)} & j=0 \end{cases} \tag{23}$$

From the expressions (22), (23) it follows that:

a) the $\cos\theta$ dependence of $\log(\epsilon\, d\sigma/d\vec{p})$ is almost linear

b) When the energy grows (y decreases) the cross section of $\pi^{\pm}$ and K^{+} steeply increases due to a vector gluon exchange in the Born approximation of QCD.

c) The ratio of K^+/K^- yield is not suppressed to such an extent as for the fragmentation mechanism, because s- or u-quarks can be from the sea of particle B (Fig.19) with no suppression ($\beta \simeq y \ll 1$) . In the Born approximation of QCD the K^+ production comes from the subprocess with spin 1 exchange and admits 6 diagrams (Fig.19) the K^- production is due to spin 0 exchange and admits 2 diagrams (one can disregard the contribution of d-quarks from the flucton due to smallness of $\tilde{d}_k/\tilde{u}_k$). Using the expression (23) one can estimate

$$\frac{K^+}{K^-} \simeq \frac{6\dfrac{Z}{A}\left\{\ln\left(\dfrac{1-x/\bar{k}}{13.36y}\right) - \dfrac{4\bar{k}+5}{(2\bar{k}+2)(2\bar{k}+3)}\right\}}{(2\bar{k}+2)(2\bar{k}+3)} \cdot \frac{(2\bar{k}+4)(2\bar{k}+5)}{(1-x/\bar{k})^2}$$

which is $\simeq 80$ for $x \simeq 1$, $y \simeq 0.002$ ($\epsilon \simeq 0.7$ GeV, E=400 GeV) for $^{181}_{73}Ta$

d) The mechanism of polarization of Λ-particles [33] is the same as for the high p_T process. The independence of polarization of the energy, of the kind of the beam and target was predicted. Moreover, the absolute values of the polarization

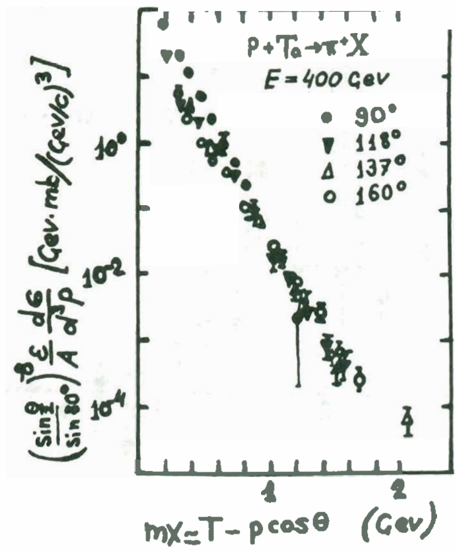

p+Ta→π⁺X
E=400 GeV
90°
118°
137°
160°
10^0
10^{-2}
10^{-4}
1
2
mX≃T−p cosθ (GeV)

Fig.18

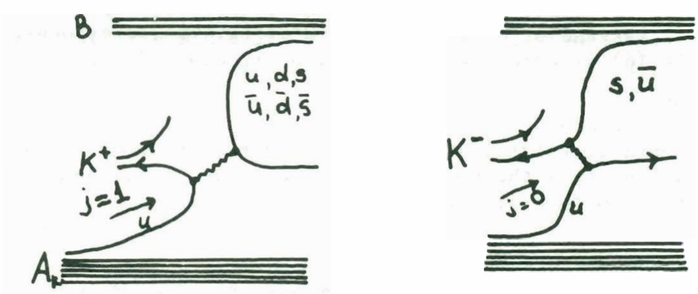

B
u,d,s
ū,d̄,s̄
K⁺
j=1
u
A
s,ū
K⁻
j=0
u

Fig.19

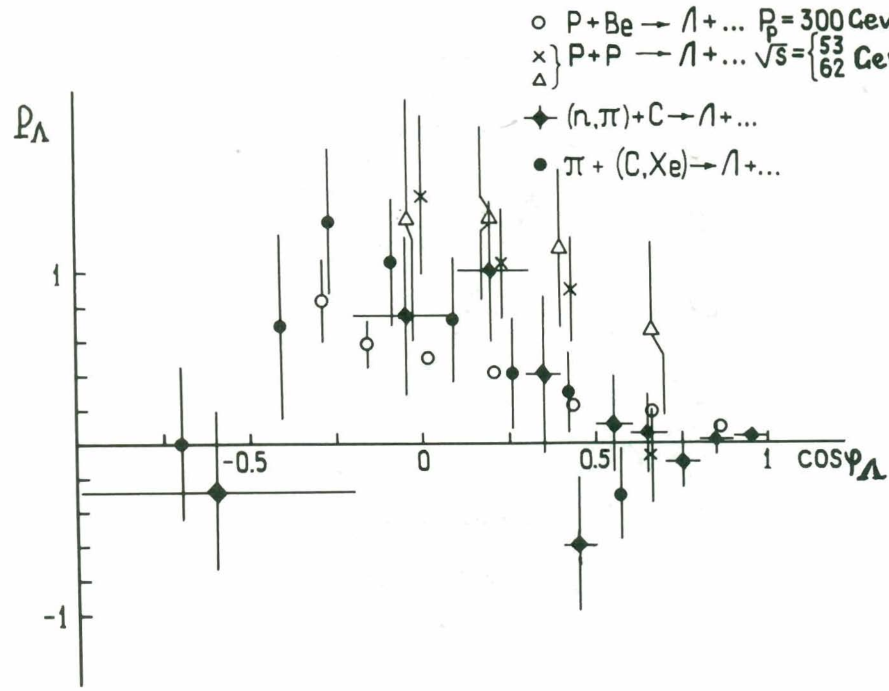


Fig.20

in both the processes are close to each other for equal values of ϕ_Λ the angle between beam and target momenta in the rest frame of the Λ-particle (Fig.20).

The main difficulty of the hard scattering model is that the usual choice of the quark scattering cross section $d\sigma/dt' \sim \tau^{-8} \sim (\sin\theta/2)^8 x^{-8}$ and the experimental distribution function $q_A(x) \sim \exp(-7x)$ leads to a too quick decrease of the cumulative production cross section with increasing of x . The effective slope in the region $x \simeq 1\div 2$ is about 12 instead of 6.78 for $\theta = 160^0$ (Fig.6). Correspondingly the $\cos\theta$ behaviour (Fig.16) disagrees where the slope is about 7.5 p instead of experimental 4.7 p.

Also, it is difficult to hope for the production of heavy fragments (N,d,t) through the quark-quark scattering mechanism (but not through $q+q \to N+\bar{q}$) because, even for the high p_T process the behaviour of the proton cross section ($\sim p_T^{-12}$) considerably differs from the pion one (p_T^{-8}).

8. DISCUSSION

So, we have to conclude that none of the models proposed gives a total description of all features of the cumulative meson production in the experimentally investigated region. As for the pion production, the most difficult question concerns the agreement of the relatively small slope of $\cos\theta$ distribution for a fixed momentum p (Fig.16) and large slope for x-distribution (Fig.5). It gives a hint that a true model should contain two exponential dependences: one on x and the other on the momentum p or momentum transfer $t=2m\epsilon$ each with a different slope. It is not difficult to check for instance, that the function

$$\exp\{-2.3t-4.7x\}=\exp\{-2.3\frac{m^2x}{\sin^2\theta/2}-4.7x\}$$

gives a good description of both distributions (solid lines in Fig.16 and 5). The dependence of such kind could naturally arise in a Regge dissociation model of the type Fig.21 or in the fragmentation model of Sect. 6 if one changes $f(p_T)\to f'(t)$.

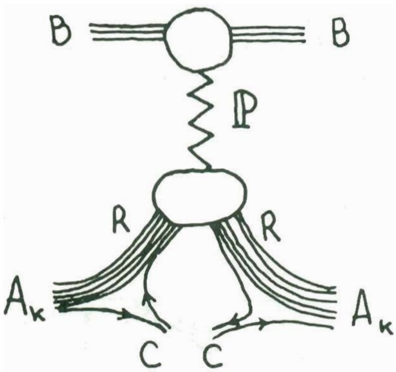


Fig.21

The role of pure nuclear effects is not yet clear except: What the role of attenuation and rescattering effects is, and why the A-dependences of light and heavy nuclei are so different. By all means, there is an influence of a surface phenomena. But what is it? It could be an inhomogeneity of the nucleon density distribution. However, it is hard to believe that this effect is so large, and it is more difficult to explain its absence for the photon beam.

The heavy fragment production process looks still more complicated. What does an astonishing A-dependence (especially, Fig.3) mean? Does it mean a knock out of fragments off the "coherent tube" or the capture of cumulative meson (or nucleon) by nucleons of the nucleus or something else? Further experiments are necessary, especially, the investigation of the heavy-fragment yield in deep inelastic lepton processes. As for the production of the cumulative protons, the essential role here belongs, surely, to the dissociation of the flucton into the proton [8].

Abundant information for understanding the cumulative production mechanism could be obtained from the polarization measurement in particular, the meson production on polarized nuclear targets. For instance, in the hard scattering picture one can expect a strong asymmetry [33] just as in high p_T processes [35].

The important role in all mechanisms belongs to the quark-parton distribution function in the nucleus. For a better investigation of this function the clearest source is deep inelastic lepton-nucleus scattering beyond $x=1$. It is the direct measurement of the nuclear structure functions, their A and x-dependences which give the most valuable and high quality information for understanding the flucton nature. It is also the basis for understanding all other high energy nuclear processes. One has to note that such measurements do not require too high momentum transfer. The momentum transfer $Q^2 \simeq 2\div3$ $(GeV/c)^2$, where the scaling regime begins, seems quite enough.

A few words, in conclusion, about the possibility of the hard quark process investigation with the use of the cumulative effect. It is connected with the possibility to reach a large r region for a heavy nuclear target at medium energy accelerators ($E=10\div70$ GeV) and rapid decrease of the dissociation mechanism contribution ($\sim \exp[-2{,}3r^2/x]$) Fig.22 presents the regions allowed kinematically for the Dubna and Serpukhov accelerators for a heavy nuclear target. The broken line shows a crude estimation of the boundary between the dissociation and the hard scattering region. The approximate values of the hard scattering process contribution are shown by the dotted lines. The broken line labelled e.g. "38" means $d\sigma \sim 10^{-38}$ cm^2. One can see that at the level of accuracy 10^{-38} cm^2 the processes with $r \simeq 13\div14$ GeV/c which are available now at ISR only could be accessible at the Serpukhov accelerator, and for 400- GeV accelerator one can reach $r \simeq 22\div23$ GeV/c.

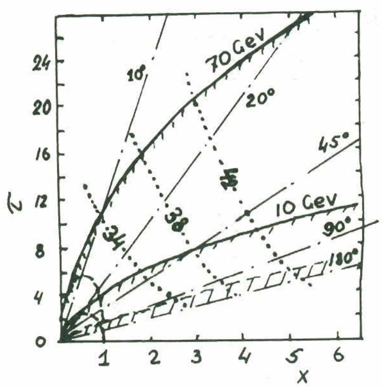


Fig.22

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