FLUCTUONS AND HIGH MOMENTUM TRANSFER IN NUCLEAR PROCESSES*

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Abstract

The report summarizes the results of a series of works made recently in JINR, which explore the hypothesis about "fluctuons", i.e. multibaryon configurations of the mass $k\, m_{nucleon}$ and correlation region of an order of elementary particles.

The probability of fluctuon-formation is calculated by the "quark bag" model. It is argued that the cumulative production is due to the hard scattering process (similar to high $p_\perp$ hadron production) of beam particle partons with partons of a fluctuon considered as a hadron made of 3k quarks.

The model explains many qualitative and quantitative features of cumulative processes: The yield of cumulative hadrons, polarization of baryons, elastic and deep inelastic ed-scattering and so on. All this gives right to consider the cumulative processes as a new source of information about quark dynamics at small distance.

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I. Fluctuons

It is as early as the fifties theoretists became interested in the appearance of "above-barrier fragments [1]. The phenomenon consists in knocking out by protons of light nuclei (fragments) from heavier nuclei when the momentum transferred to a light nucleus is much larger than the binding energy of this nucleus.

At the same time, the hypothesis[2] has been proposed that a large momentum can be transferred to a complex system of nucleons as a whole only when at the moment of collision with an incident particle a number of internuclear nucleons are inside a small volume, due to quantum fluctuations, and takes the momentum transfer as a unique particle with mass $M_k = km$ (m is the nucleon mass, k the number of nucleons in the group). A multi-nucleon formation of this type has recently been called as a "fluctuon".

With this hypothesis, a satisfactory agreement[2] has been obtained with the known data on yield of "above-barrier fragments". It has been found that the size of fluctuon is comparable with the size of the repulsion core and in some coses gets the nucleon size. At that time, these things were somewhat amasing, however, now it is clear that this mechanism of fluctuon formation does not contradict the modern ideas on particle structure and the fluctuons should be treated at the quark level. It is just a way to link the elementary particle physics with the nuclear physics at large momenta transferred and to investigate multi-quark systems.

The existence of fluctuons is now justified by the cumulative production of particles[3,4,5] with a certain number of specific properties, as well as the behaviour of nuclear electromagnetic form factors at large momentum transfers etc.

2. Cumulative Processes

An extensive information became available from the cumulative hadron production, i.e. from the inclusive process $A+B\to C+X$ in the collision of fast particles with nucleus in the kinematic region inaccessible in the collision of that particle with the nucleon at rest. As is known[6], these processes exhibit the following features:

a) Nuclear scaling, i.e. independence of invariant cross sections on the incident particle energy E;

b) Exponential drop of the yield of cumulative particles with energy ε and the grouth of exponential slope with the particle increasing mass;

c) Anisotropy of the cross section in the emission angle θ in the lab.system at large momenta p and isotropy at small momenta;

d) Power dependence of the cross section on atomic number $d\sigma \sim A^n$ the power n for pions being changed from $2/3$ at low energies to 1.2 at high energies ($\sim$1 Gev) and for heqvier particles (p,d,t) $n \approx 1.3 \div 2$;

e) A significant correlation ($\sim$2) at 180° with respect to the angle between the cumulative and any charged particle.

The experimental data recently obtained confirm and determine more accurately these properties. Among them, new measurements of polarization of cumulative Λ-particles/8,9/ deserve a particular attention for the following reasons:

f) Polarization is very large ($\approx$100%) around $\Theta \simeq 90°$, and decreases with growing and decreasing angle;

g) In the range from 2.8 to 8 GeV no dependence on E is observed.

As is known, the above listed properties do not support the traditional mechanisms like Fermi-motion and multiple scattering on nuclear nucleons as possible candidates for the cumulative process. The first of them fails to explain the fact that the cumulative particles are produced far of the region admissible by the mean nuclear field, i.e. by the momenta of an order of $1.5 \div 2 \text{ fm}^{-1}$. Also, the Fermi motion cannot account for such a strong dependence on the atomic number.

As an example, we show in Fig. 1 the cross section of $p + {}^{12}C \rightarrow \pi + X$ in the impulse approximation/10/. Curve 1 is the pion production cross section on nucleons at rest, curve 2 stands for the Fermi motion of nucleons in the nucleus-target, curve 3 represents the effects of relativization in the wave function of the nucleon bound state from Fig. 1 it is clear that the $4 \div 5$ orders discrepancy of theoretical curves with experiment is conditioned by another mechanism of pion production.

On the other hand, the explanation of the large-momentum component by the multi-scattering mechanism requires a multiplicity much higher than the number of nucleons along the trajectory of a scattered particle./11/

The hypothesis of the so-called few-nucleon correlations /12/, proposed recently, also seems to be unsatisfactory. The slope of pion spectrum should be larger than that for nucleons because the cumulative meson, according to this hypothesis is product of the cumulative proton fragmentation. Also the experiment displays no correlation between the cumulative pion and proton at that same direction.

The interpretation of the cumulative effect within the hypothesis on fluctuons implies the following problems:

1) what is the probability of production of this multi-nucleon system in a nucleus?

2) In what way does it interact with the incident particle?

First, let us dwell on the second problem. The process $A+B\to C+X$ depends on the three invariant variables

$$s = 2p_A p_B = 2mE$$
$$t = -2p_A p_C = -2m\mathcal{E}$$
$$u = -2p_B p_C = -2\mathcal{E}(\mathcal{E}-p\cos\theta)$$

where E is the energy of an incident particle, $\mathcal{E}$ and p the energy, momentum, and angle of the cumulative particle, resp. The kinematical boundary of cumulative process is defined as follows ($E \gg \mathcal{E}, m$)

$$k \approx \frac{\mathcal{E}-p\cos\theta}{m} > 1 \qquad (1)$$

It can be observed that in this range all variables s, t, u and $\rho = \frac{ut}{s}$ are larger than the hadron masses like in the processes with large $p_\perp$ (where $\rho = m_\perp^2$). For this reason, it is natural to assume[13,6] that the cumulative process at ρ large enough is defined by the same mechanism as the large $P_\perp$ process, i.e. by the hard binary collision of fluctuon's parton with that of the incident particle (Fig. 2). (The same result follows from the consideration of asymptotics of QFT Feynman diagrams for the cumulative process).

As usual, the invariant cross section is of the form

$$\varepsilon \frac{d\sigma_A}{d^3p} = \int d\gamma\, d\Delta\; Q_{A/a}(\alpha) Q_{B/b}(\beta) \frac{1}{\pi} \frac{d\sigma}{dt'}(s',t')\, D_{c/C}(\gamma) \tag{2}$$

where

$$Q_{A/a}(\alpha) = \sum_{q=1}^{A} P_q^A\, Q_{qN/a}\left(\frac{\alpha}{q}\right)$$

$$\alpha = \frac{x_1}{\gamma}(1+e^{\Delta}) \qquad x_1 = -\frac{u}{s} \simeq k$$

$$\beta = \frac{x_2}{\gamma}(1+e^{-\Delta}) \qquad x_2 = -\frac{t}{s} \simeq \frac{\varepsilon}{E}$$

$$-\ln\frac{\gamma - x_1}{x_1} \le \Delta \le \ln\frac{\gamma - x_2}{x_2}$$

with P_q^A the probability of of an q-nucleon fluctuon and $Q_{qN/a}$ the probability of its fragmentation into parton a.

Since β is rather small in magnitude, the fragmentation of B into antiquark b is not suppressed. Therefore the direct production of the cumulative meson (and nucleon) (Fig. 3) seems the most probable (especially due to trigger bias), i.e. $D(\gamma) \simeq \delta(\gamma - 1)$. Because of the cross section $d\sigma/dt'$ is concentrated around the c.m. rapidity difference $\Delta \simeq 0$, $\beta \simeq x_2, \alpha \simeq x_1$ and

$$d\sigma_A \simeq \sum_{q=1}^{A} P_q^A\, d\sigma_N\left(x_2, \frac{x_1}{q}\right)\left(1 - \frac{x_1}{q}\right)^{6(q-1)} \tag{2a}$$

Let us recall how this mechanism fulfills the above listed properties.

For the probability P_q^A we first take the classical ideal gas formula

$$P_q^A = \left\{ {A \atop q} \right\} \left(\frac{V_f}{V_A} \right)^{q-1} \tag{3}$$

where V_A is the nucleus volume $V_A = V_0 A$, and V_f is a fluctuon volume, i.e. a characteristic volume inside which the nucleons can be considered as coherent. The probability of fragmentation $Q_{qN/a}$ will be chosen in the form: $Q \sim \left(1 - \frac{x_1}{q}\right)^{2n_{pass}-1}$ $n_{pass} = 3q - n_a$ (n_a is the number of quarks in parton a). On summing over q by the steepest descents method we get

$$\mathcal{E} \frac{d\sigma}{d^3p} \simeq \left(\frac{E}{\varepsilon}\right)^{\alpha_P(0)} \left(\frac{V_A}{V_f}\right) \varphi(\varepsilon) \exp\left\{-k\, B\left(\ln \frac{k V_A}{A V_f} c\right)\right\} \tag{4}$$

where $B(L)$ is a certain monotone function for $L > 0$, such that $B(0) = 0$ and $B(L) \sim L$ for $L \to \infty$. (Its shape depends on the way of the fluctuon formation). It is seen that if $\alpha_P(0) \simeq 1$ the cross section does not depend on E; with growing mass of the incident particle the slope, B , increases; the cross section is isotropic for $p \ll \mathcal{E}$ and decreases with increasing angle for $p \approx \mathcal{E}$.

Now, let us consider the polarization of Λ -particles[15]. The hard scattering formula (2) can easily be generalized to the density matrix which gives immediately

$$P = \frac{\int Q_{A/a}(\alpha)\, Q_{B/b}(\beta)\, X_2(\Delta)\, d\Delta}{\int Q_{A/a}(\alpha)\, Q_{B/b}(\beta)\, X_1(\Delta)\, d\Delta} = I(x_1, x_2) \sin\varphi$$

after scaling assumption $\rho_{\mu\nu}\frac{d\sigma}{dt'} \sim \frac{1}{(s')^{m/2}}\left[\chi_1\left(\frac{s'}{t'}\right) + (\vec{\sigma}\vec{n})\,\chi_2\left(\frac{s'}{t'}\right)\sin\varphi\right]$ (φ is the angle between momenta of the beam and target in the rest frame of Λ -particle, $\vec{n}$ is the normal to the scattering plane).

The analysis of large $p_\perp$ -processes indicates that the functions χ_1 and χ_2 quite rapidly decrease with growing $|\Delta|$ $(< e^{-|\Delta|})$ therefore $\mathcal{I}$ in the fragmentation region of a target $(x_1 \approx 1\ ,\ x_2 \ll 1)$ weakly depends both on its variables and on the type of a target (and incident particle). This gives a possibility to compare the Λ -particle polarization in the proton-fragmentation region/16/ for $E = 300$ GeV with the polarization of cumulative Λ-particles (i.e. nucleus fragmentation region) at E = 2.8 GeV at the same value of $\sin\varphi$ The comparison is shown in Fig. 4 and indicates that the fluctuon behaves like a multiquark hadron.

The data/9/ submitted to this Conference on polarization of cumulative Λ -particles at 4 and 8.4 GeV support one of the basic prediction of the hard scattering mechanism, the independence of polarization on the incident particle energy.

Let us consider now the A-dependence of the cross section. As is seen from (4), this characteristic depends on what is meant by V_f , i.e. what is the fluctuon? Here two points of view are admissible:

A) The fluctuon is a quasistable formation with definite binding energy and life-time (like a broad resonance state). In this case the volume V_f can be treated as a volume of a sphere in the rest frame of a nucleus with radius of an order of the effective range of nuclear forces $(\approx 1/m_\rho)$. Then $\frac{V_A}{V_f} \sim A$

and cross section increases proportionaly to A . The reduction of the exponent n down to 2/3 is due to the screening by the other nuclear nucleon. However, it is clearly difficult to explain in this case the exponent $n > 1$

B) The fluctuon is an instantaneous fluctuation of coherent without definite energy when several nucleons are simultaneously concentrated at a distance smaller than the "coherence radius" ($\approx 1/m_f$) from the view point of the incident particle. This means that when the Lorentz-factor is large, the fluctuon is formed by all nucleons concentrated in the cylindrical tube with radius $1/m_\rho$. In this case $(V_A/V_f) \sim A^{2/3}$ and the exponent n for the cross section $n - 2/3 \sim \frac{1}{3} K$, i.e. increases with growing $k = \frac{\varepsilon - p\cos\theta}{m}$. For heavy particles it can reach large values. However, the "flattening" of n probably observed[3,5] for pions is not explained yet.

Quantitative calculations on the basis of formula (2a) and known nucleon cross sections $d\sigma_N$ were performed in paper[10]. The comparison with experiment is drawn in Figs. 5,6. Figure 5 shows the contribution of individual fluctuons, whereas Fig. 6 gives the comparison for a series of nuclei. The size of the fluctuon of type A appears to be $r_f \sim 0.7$ fm, i.e. of order of the radius of the NN force repulsive core.

Analogously, by using (2a) the nuclear form factor was calculated. For deuteron one has:

$$F = F_d^{I} + \beta_2^2 F_d^{II}$$

where F_d^{II} is the deuteron form factor in the fluctuon state treated as a six-quark object. Consequently, by the quark counting rule[17] $F \sim q^{-10}$ and can be given in a different parametrized form[18]. The results of calculation are shown in Fig. 7. It is interesting to note that the probability of fluctuon formation with $q = 2$ in nuclei $(\approx 6\%)$, is in agreement with the result of analysis of the deuteron form factor, where $P_2^2 \approx 8\%$.

3. The Fluctuon Formation

Let us now consider the formation of fluctuon of the type A, i.e. estimate the probability of its existence as a multi-baryon configuration in nucleus. We use for this the quark-bag model. To start with, we define the probability in the following form:

$$P_q^A = b_q^A D_q$$

where b_q^A is the probability of finding in nucleus A of a q -nucleon ("non-compressed") cluster, D_q is the probability of finding of that cluster in the state of fluctuon compression. In fact, D_q is the probability of phase transition of q nucleons into state of 3 -quark object. The value b_q^A can be calculated by the usual methods of nuclear physics. The value is defined as an integral over the fluctuon volume[2]

$$D_q = \int_{V_f} |\psi(1 \cdots q)|^2 d\tau$$

where ψ is the wave function of q- nucleons in their c.m.s. and is a solution of the wave equation. And finally, the probability of penetration of nucleons at short distances is determined by a given repulsion potential in that region of space. We will evaluate this multi-particle core as a difference between the energy of the 3 -quark hadron bag and mass of the q -nucleon cluster:

$$V_q = E(3q) - qmc^2$$

To calculate $E(3q)$ we use the spherical MIT bag model [19] which defines the mass of the 3-quark system as follows

$$E(3q) = E_V + E_0 + E_Q + E_M$$

Here E_V - is the energy of external pressure which prevents quarks to leave the bag, E_0 is the "zero energy" of the quark field, E_Q the free and kinetic energy of quarks, E_M the quark interaction energy. The calculation gives $V_2 = 0.27$ GeV, $V_3 = 0.8$ GeV, $V_4 = 0.99$ GeV. Therefore, the existence of multi-baryon configurations in nucleus results as a strong multi-particle repulsion at short distances which do not reduced to the pure pair interactions (Fig. 8).

Figure 9 represents the calculation[11] of multi-baryon configurations obtained with the above mentioned potentials. As is seen, the probability D_q rapidly decreases with growing q. The abrupt change in D_q when passing from $q=4$ to $q=5$ is due to the Pauli principle which forbids all five nucleons to be in the small volume simultaneously. The probability of the two-baryon system in deuteron, 8÷9%, is in good agreement with e-d elastic scattering data and earlier calculations[20]. The calculated D_q can be compared with the results of analysis of the particle cumulative production. The crosses in Fig. 9 represents the quantity

$$(D_q)_{exp} = \frac{(P_q^A)_{exp}}{b_q^A} \quad \text{when } q = k$$

It is seen that the calculated probabilities is in agreement with experiment.

Conclusion

From our consideration we conclude that the hypothesis on fluctuons provides a good quantitative and qualitative description of main properties of the cumulative effect. We suppose that the study of such quark formations can be important in several theoretical aspects. First, it gives a possibility to investigate the quark systems with alternative number of quarks, i.e. it may help one to better understand the problem of quark confinement. In particular, an interesting question there arises: how many quarks may be put into a bag? What occurs with the bag size with increasing number of quarks?

Second, these dense formations allow the study the large-transfer, momentum processes even at intermediate-energy accelerators. So, at the Dubna accelerator one may produce in principle, backward pions with energy $\mathcal{E} \simeq 5$ GeV what is equivalent (in ρ) to the transverse momenta $p_\perp \approx 10$ GeV/c presently accessible at ISR only. It is probably unrealistic task because of a very small cross sections. However, we can only quess now about the rate of decrease of the cross section above $k \approx 2 \div 3$ The nearest experimental task is to give further more clear arguments in favour of the fluctuons in nuclei. Among them especially informative seems to be a correlation measurement of the same kind as in high $p_\perp$ region and polarization and assymetry experiment in the energy range of Serpukhov-Batavia. These can bring a new evidence for the parton hard scattering picture.

As for the nature of fluctuons here the most informative seems to be a precise A-dependence measurement especially in deep inelastic lepton-hadron scattering (in particular in NA-4 experiment at SPS). The yield of a heavy framents is also interesting for this aim.

We are greatly convinced, that in cumulative production we met with a new phenomena of Nature which deserves more attention of theoreticians and experimentalists.

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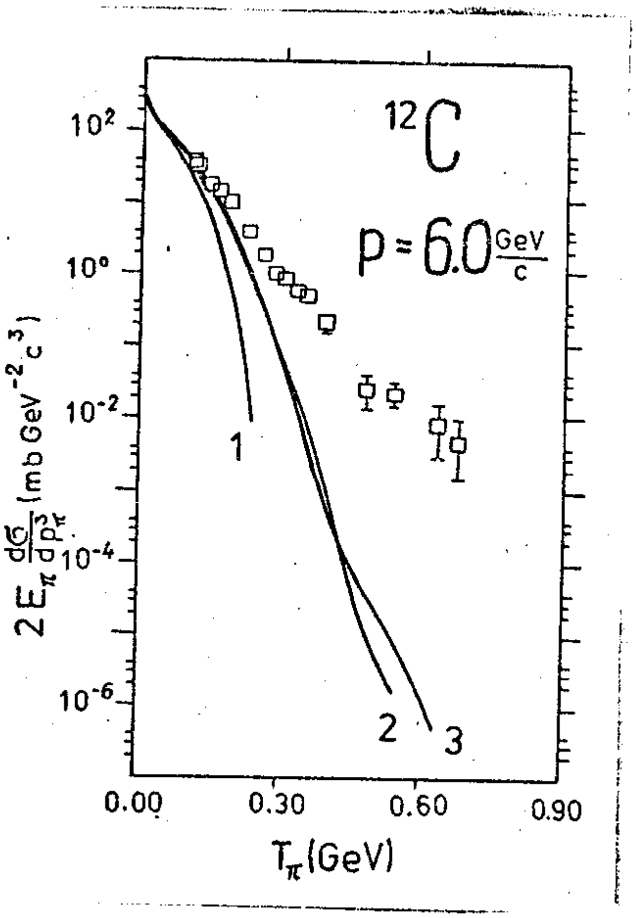


Fig 1.

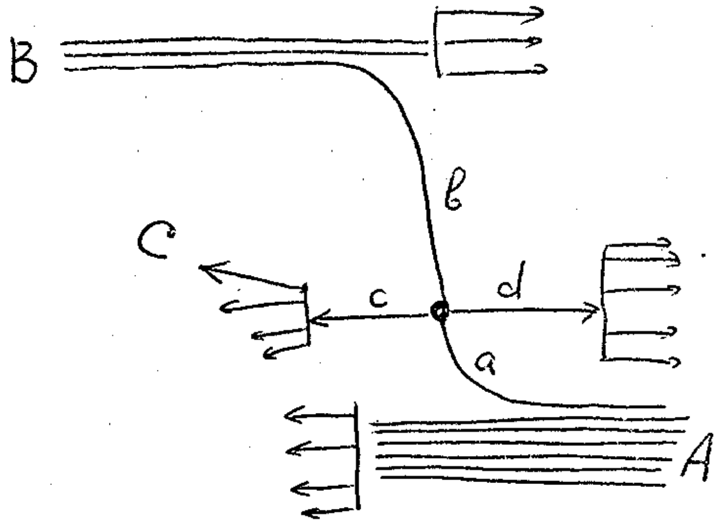


Fig. 2.

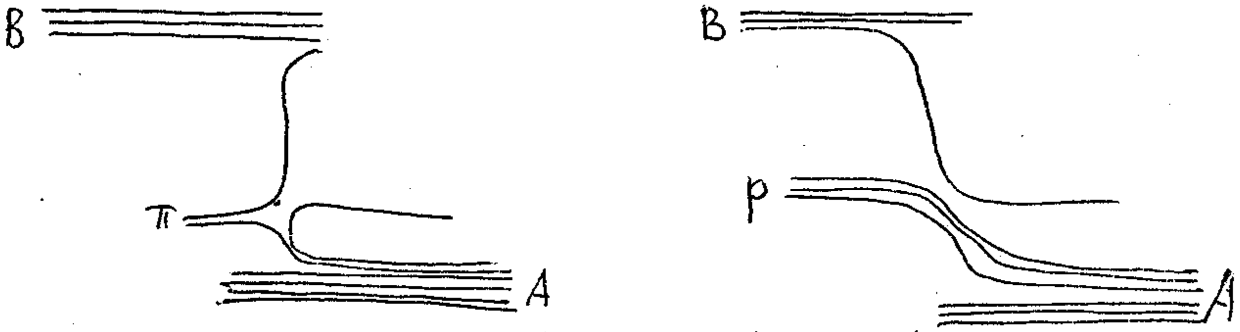


Fig. 3

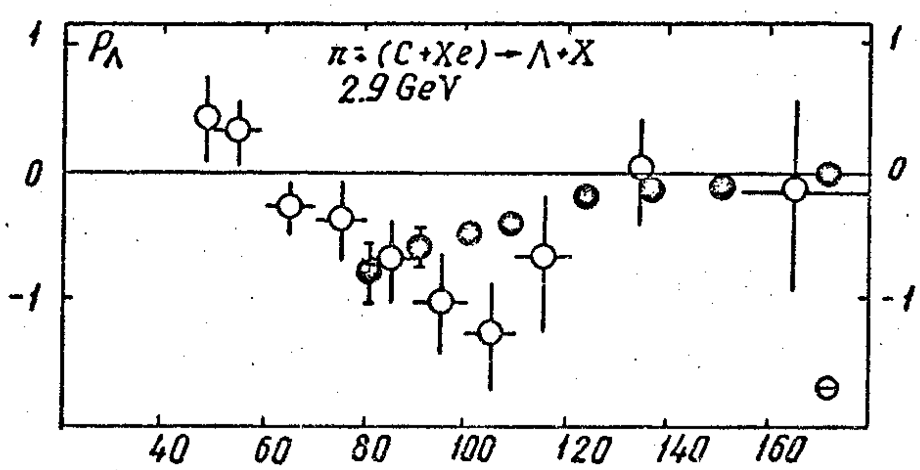


Fig. 4

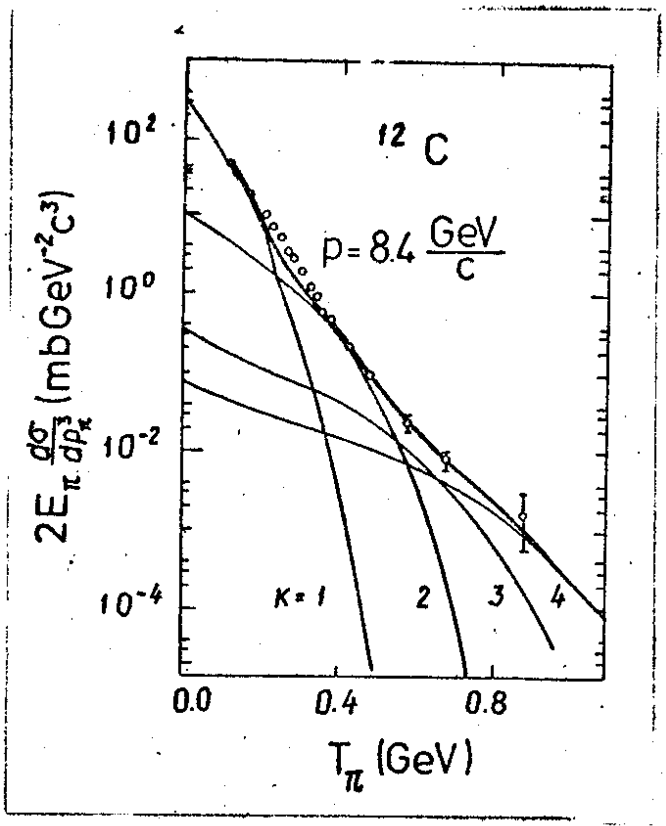


Fig. 5

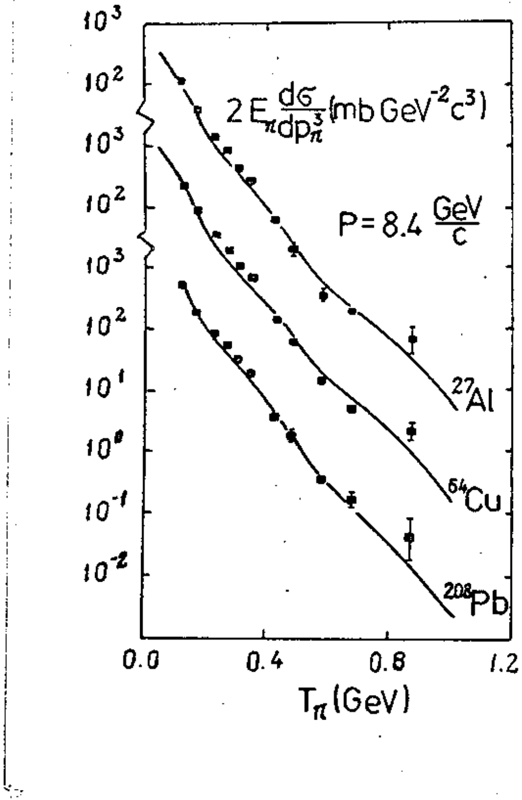


Fig. 6

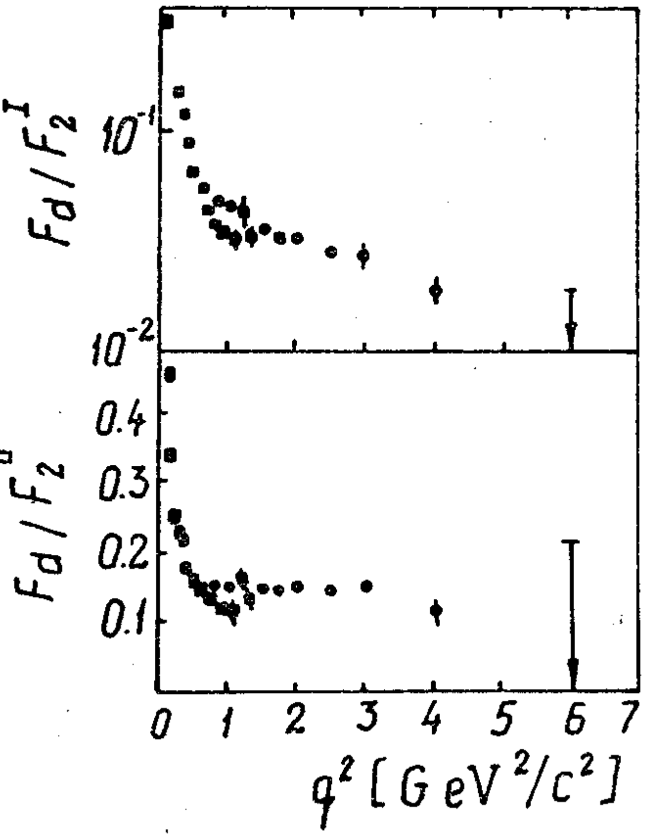


Fig. 7

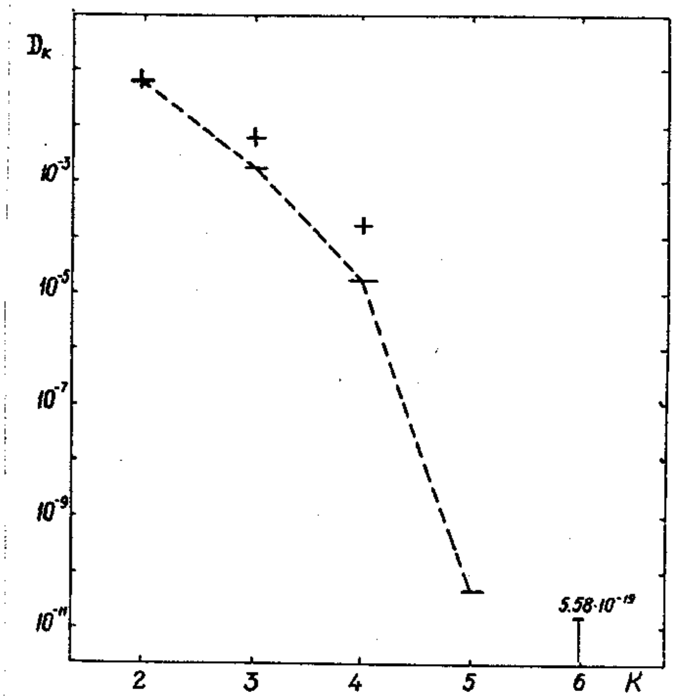
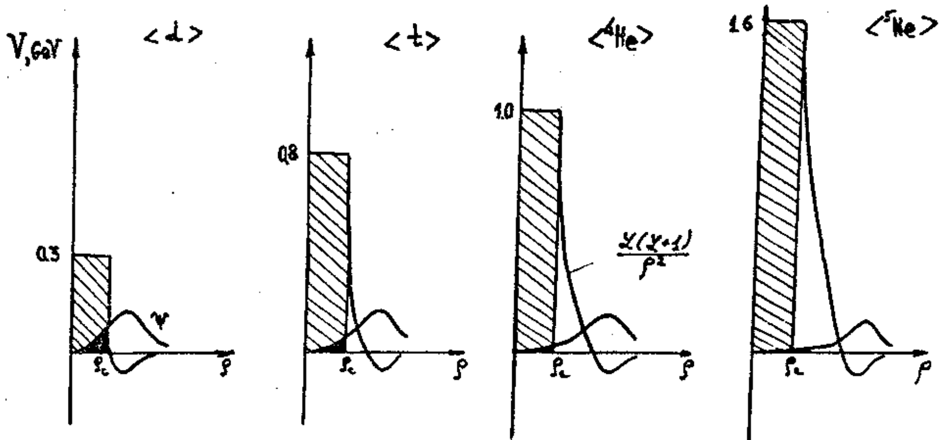


Fig. 9



$$V_B \simeq E(\kappa) - \kappa M c^2 \; ; \quad V_{eff} \simeq V_B + \frac{l(l+1)}{\rho^2} .$$

Fig. 8.