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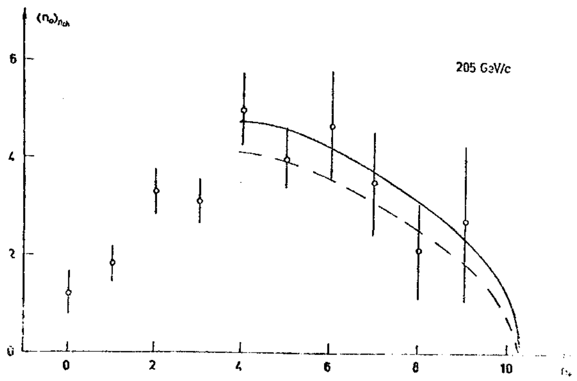

Fig. 1. The associated average neutral multiplicity $\langle n_o \rangle_{n_{ch}}$ in pp collisions, at 205 GeV. The curves are calculated by Kirschner/9/.

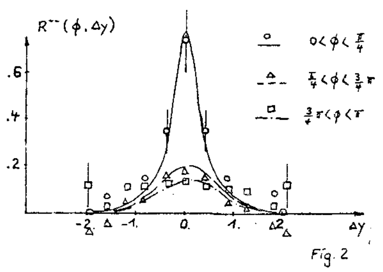

Fig. 2. Divided correlation function R^{--} as function of Δy for different $\Delta\phi$ ranges. The data are due to Bisnas et al./13/. The curves are calculated by Kripfganz/15/ and similarly by Ranft et al./10/.

P L E N A R Y   R E P O R T

MECHANISMS OF MULTIPLE PRODUCTION PROCESSES

I.M.Dremin

FIAN, USSR

1. Introduction

My object is to speak about theoretical approaches to multiple production processes. The variety of the approaches enforces me to start with some classification, this classification being, of course, rather relative.

A large number of models proceeds from the notion about common excited system produced by colliding hadrons. This class of models, including hydrodynamical, statistical, thermodynamical and statistical bootstrap models will be referred to hereafter as H (hydrodynamics) models.

Sometimes the production process is conjectured as due to excitement and decay of two colliding particles, that is two systems are assumed to be formed, originating from two initial hadrons. The fragmentation, bremsstrahlung and inelastic diffraction models are pertained to this F (fragmentation) group.

The largest group of models describes the multiple production process as a result of formation of many excited centers. The typical example is the multiperipheral model (so this group is referred to as M group), which is connected closely with inclusive Regge approach, parton description, independent cluster production model and uncorrelated jet models. An eikonal prescription is used widely to take into account rescattering effects.

An interesting direction is given by the papers where attempt is made to interrelate the mechanism of multiple production with internal structure of particles, that is with their constituents (C-group)-quarks, gluons,etc.

Besides the models there are phenomenological (P group) attempts to connect different features of multiple production.

Experimental data indicate the existence of leading and pionization particles thus giving an evidence for applications of different models.

The idea of fragmentation can be applied to leading particles. Such particles appear in peripheral blocks of multiperipheral diagrams and they are viewed as being formed by quarks which fly through in constituent picture.

At the same time one can attempt to use statistical approach to the particles in pionization region (to the whole set of these particles or to some subunits which can be produced by multiperipheral or some other mechanism). So as a rule one deals with many-component description of multiple production processes.

There is some periodicity in the development of the theory of multiple production. Approximately once a decade ideas appear influencing considerably the direction of research.

In 1950 Fermi's paper pushed forward the statistical approach which was later developed by Landau as a hydrodynamical theory. In 1960 peripheral diagrams became very popular giving rise to multiperipheral theory. In 1970 the new development to this approach was stimulated by ideas of inclusive description and scaling in the frames of parton and fragmentation models.

As the decade has not yet passed and new theoretical ideas have not been developed I'll confine myself mainly to giving an account of recent developments of approaches mentioned above to show to which extent they can accomodate continuously increasing flow of new experimental data.

II. Statistical and hydrodynamical approach

Experimantal data on inclusive spectra at high energies have raised interest in statistical and hydrodynamical models during recent years. The point is that only these models explain naturally the exponential damping of transverse momenta of produced particles and go away from somewhat monotonous plateau picture for rapidity distributions.

An account of these models was given at many conferences. So, after short introduction, I'll give a review of only those papers, which appeared recently.

The basic assumption of statistical approach to multiple production /1,2/ is that the subsystem produced at hadron collision comes quickly to the state of thermodynamical equilibrium due to strong interaction. The three stages can be distinguished.

1. Initial stage of mixing and forming of highly excited system. 2. Hydrodynamical stage of isoentropic expansion. 3. Final stage when system breaks-up into secondary particles.

To describe completely the evolution of the system it is necessary to specify:

1. Energy-momentum conservation. 2. Statistical momentum distribution. 3. State equation. 4. Chemical potential. 5. Initial conditions and break-up prescription.

As a pattern to compare with I'll give a summary of Landau hydrodynamical model. Energy-momentum conservation is given by

$$\partial T_{ik} / \partial x_k = 0 \qquad (1)$$

where

$$T_{ik} = (\varepsilon + p)\, u_i u_k - p\, g_{ik} \qquad (2)$$

is energy-momentum tensor of ideal relativistic fluid, ε is density of energy, p is the pressure, u_i -four-velocity, $g_{00} = -g_{ii} = 1$.

Pion momentum distribution is given by Bose distribution in an accompanying frame:

$$dN = \frac{gV}{(2\pi)^3} \cdot \frac{d^3q}{e^{E/T} - 1} \qquad (3)$$

where $E = \sqrt{q^2 + m^2}$ is the energy of the paricle, g is the number of its spin and charge degrees of fredom ($g = 3$ for the pion), T is the temperature and V is the volume of the final state.

State equation is taken in the form

$$p = \varepsilon / 3 \qquad (4)$$

valid for three-dimensional gas of relativistic parti...

...hemical potential is

$$\mu = 0 \qquad (5)$$

So the number of particles is not fixed but have to be determined by equilibrium condition (similarly to the case of the black-body radiation), that is the thermodynamical potential is zero,

$$\mathcal{E} - TS + p = 0 \qquad (6)$$

(S is the entropy density). From here one can easily obtain that $\mathcal{E} = \varkappa T^4$.

It is assumed that at the initial moment the hadron system is a disk at rest (v =0 at t =0) the redius of the disk being $\sim \frac{1}{m_\pi}$ and its thickness is $\sim \frac{1}{m_\pi} \cdot \frac{m}{E_0}$ (m_π, m - pion and nucleon, masses, E_0 -CMS energy). The expansion of the system is controlled by eqs. (1.)-(5) and a break-up into free particles occurs when temperature becomes of the order of m_π .

The physical consequences of this picture are well known. The mean multiplicity increases like $S^{1/4}$, the rapidity distribution is well approximated by Gaussian exponent,etc.

The following directions of its development can be noted:

1) attempts to give a more detailed description resembling kinetic approach and closely connected with non-linear Lagrangians of the field theory; 2)incorporating the information on internal structure of colliding particles; 3) revision of the points 3)-5) mentioned above; 4) detailed comparison with experimental data.

In more general kinetic approach[4,5] (leading in some limit to hydrodynamics the Wigner distribution function is used:

$$F(p,R) = \int d^4 z \, e^{ipz} \langle \Psi_{in} | \phi(R-\tfrac{z}{2}) \phi(R+\tfrac{z}{2}) | \Psi_{in} \rangle \quad (7)$$

where ϕ are the field operators, averaging is performed over in-states and Heisenberg picture is used. Accepting Ψ_{in} to be two-particle states and using the relation of unclusive spectra to many-particle amplitudes it is easy to see that the single-particle inclusive spectrum can be expressed in terms of Wigner F -function:

$$2\omega \frac{d^3 N}{d^3 p} = \frac{(p^2-\mu^2)^2}{(2\pi)^3} F(p, q=0) \qquad (8)$$

At the same time, F -function can be shown to obey the kinetic-type equations with nonlinear term depending on the form of the Lagrangian. In some approximation a transition to hydrodynamical theory can be demonstrated[5]. The connection of nonlinear Lagrangians with hydrodynamical theory parameters was considered many years ago[6]. Now it is suggested to establish this connection in the frame of kinetic approach where Regge-type inclusive description can be incorporated to.

Hydrodynamical theory is usually supposed to give a "macroscopic description" of the extension process as the density of the matter is too strong to say about individual particles. If one accepts a hypothesis of pointlike constituents of hadrons, then it is possible to give[7,8] a treatment of hydrodynamics which suggests that just statistical properties of constituents (but not dynamics of their interaction) are responsible for basic features of the process, such as one-particle distributions, for example.

The presence of phase transition is the characteristic feature of a statistical approach in which the thermodynamical properties of the system are expressed through S-matrix of the particles constituting the system[10,11]. The state equation is different from (4) in this case and has the form $p = \frac{\mathcal{E}}{5}$ at high energies. Similar picture, with the presence of phase transition, arises when one attempts to use the results of field theory models with symmetry breaking in high energy physics[9].

Let us note that phenomenological attempts to modify the state equation had been undertaken earlier[6,12-16]. In particular the state equation

$$p = c_0^2 \, \mathcal{E} \qquad (9)$$

was investigated with arbitrary constant value of C_o. The value of C_o was connected with a power of nonlinear Lagrangian [6] $C_o^2 = \frac{1}{2n-1}$ for $L_{\ell \delta} \approx \lambda \left(\frac{\partial}{\partial x_k} \varphi \right)^{2n}$. For this case $p \sim T^{\frac{c_o^2+1}{c_o^2}}$, $S \sim T^{1/c_o^2}$, $\bar{n} = E_{cm}^{(1-c_o^2)/(1+c_o^2)}$.

Calculation [13,14] of C_o was performed taking into account a set of known resonances. The equations used are the following

$$c_o^2 \equiv \frac{\partial p}{\partial \varepsilon} \; ; \; p = \frac{1}{3} \sum_i \int \frac{d^3q \cdot V g_i}{(2\pi)^3} \frac{q^2}{E_i} \left[e^{E_i/T} - 1 \right]^{-1} \quad (10)$$

$$\varepsilon = \sum_i \int \frac{d^3q \cdot V g_i}{(2\pi)^3} \cdot E_i \left[e^{E_i/T} - 1 \right]^{-1} \quad (11)$$

where sums are taken over resonances. The results are given in Fig.1.

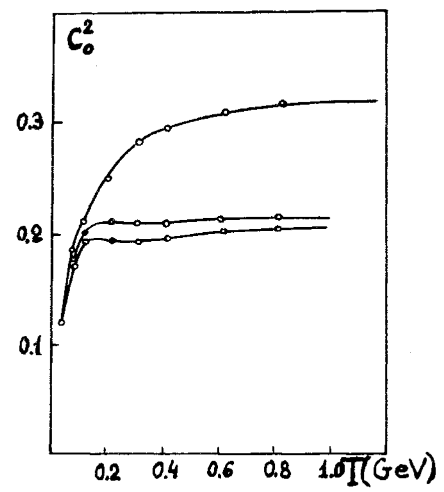

Fig. 1.
The T-dependence of C_o^2 [14]. The upper curve was obtained without resonance contribution in (10), (11). The lower curves are for different sets of resonances.

One can see that C_o^2 is close to 1/5 at high temperature. It is interesting to note that comparison with experimental data also suggests the same value for C_o^2 [13,14] in order to obtain the best agreement between theory and experiment.

Quantitative comparison with experiment [13-15, 17-31] will be considered below. Here I wish only to emphasize that one needs to take a special care when selecting a system (or subsystem) to apply a statistical treatment [15]. It is connected mainly with peripheral nature of collisions displaying through appearence of leading particles whose treatment is far from being definite in the frames of statistical approach (compare [12,13]).

At the same time it is the peripheral character of interactions that underlies fragmentation and multiperipheral models.

III. Fragmentation Models

According to fragmentation models [32-37] the inelastic interaction of two hadrons proceeds through excitation of one or both of them whith subsequent decay into many particles. The energy and the angular momentum could be transferred from one hadron to another. Other internal quantum numbers of an excited system coincide with those of its parent hadron.

The formation of two centers of particle emission, each of which reminds its primary hadron, is a distinctive feature of fragmentation models.

Not very much work was done on F -models since 72-74-Conferences. The reason is that even though their particular realizations [36,37] can get a reasonable behaviour of the mean multiplicity

$$\langle n \rangle \sim \int^{\sqrt{s}} \rho(M)\, n_e(M)\, dM \sim \int^{\sqrt{s}} M^{-2} M\, dM \sim \ln s \quad (12)$$

they predict rather strong fluctuations in individual events

$$f_2 = \langle n(n-1) \rangle - \langle n \rangle^2 \sim \int^{\sim\sqrt{s}} \rho(M)\, n_e^2(M)\, dM \sim \sqrt{s} \quad (13)$$

Here $\rho(M)$ is the probability of production of an excited state of mass M and $n_e(M)$ is its decay multiplicity.

The missing mass dependence of the associated multiplicity differs in the experiment from the behaviour of $n_e(M)$.

The above-mentioned as well as some other features of the fragmentation model are in favour of the opinion that its particular realizations could be if at all, applied for very restricted energy region[37], or just asymptotically [36].

Another feature of F -models is the presence of long-range correlations at high energies. Even if one assumes the independent emission of clusters with the rapidity plateau within the bremsstrahlung model[38-40] the long-range correlations of nucleons persist. But such a model is surely quite similar to multiperipheral ones.

The fragmentation ideas combined with region exchange are widely used for the description of diffractive dissociation processes which are described in Kaidalov's report.

IV. Multiperipheral Scheme

The production of many centers of particle emission is a general feature of the multiperipheral approach[41-43]. It follows from the main assumption about small transferred momenta. The graph representation of the process is shown in Fig.2. At large enough energies the multiperipheral chain is long and one can use the integral equation for total cross sections[41-43]:

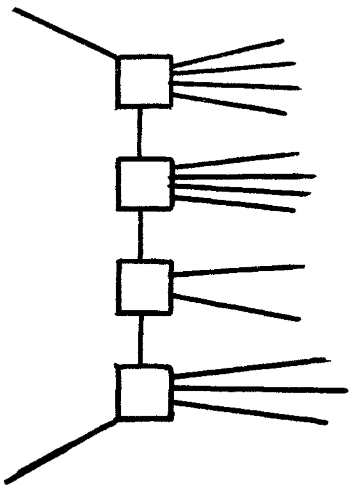

Fig. 2.
The multiperipheral graph.

$$\sigma = \bar{\sigma} + [\bar{\sigma}, \sigma] \qquad (14)$$

where

$$[\bar{\sigma}, \sigma] \simeq \frac{1}{(\ell\pi)^3 S^2}\int \frac{dK^2 S_1 dS_1 S_2 dS_2}{(K^2+\mu^2)^2}\, \bar{\sigma}(S_1, K^2)\, \sigma(S_2, K^2) \qquad (15)$$

The function $\bar{\sigma}$ is the total cross-section of all nonperipheral processes plus interference terms of those processes with peripheral ones. Therefore, it can contain the resonance production and elastic diffraction as well as some part of the inelastic processes.

Similar equations could be derived[44] for inclusive spectra (for example, for $F_1 = E\frac{d^3\sigma}{d^3p}$):

$$F_1 = \bar{F}_1 + [\bar{F}_1, \sigma] + [\bar{\sigma}, F_1] \qquad (16)$$

where $\bar{F}_1$ is the single-particle inclusive spectrum of particles produced in non-peripheral processes.

The solution of eq. (16)

$$F_1 = \bar{F}_1 + [\bar{F}_1, \sigma] + [\sigma, \bar{F}_1] + [\sigma, [\bar{F}_1, \sigma]] \qquad (17)$$

consists of the sum of contributions from non-peripheral processes (the first term), from the fragmentation of colliding hadrons (the second and third term) and from the pionization component (the last term) - see Fig. 3.

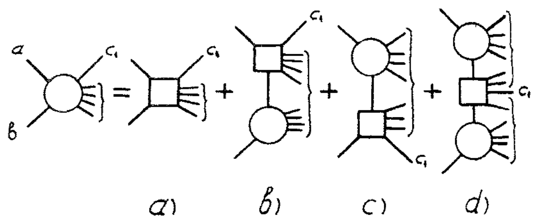

Fig. 3.
Inclusive multiperipheral graphs.

Thus the multiperipheral approach (14), (16) incorporates the multicomponent structure of inelastic processes.

The main advantage of the graphical representation is both in the clear-cut interpretation of inelastic processes and especially in its connection with the main parameters of elastic scattering (as well as with the amplitudes of processes $3 \leftrightarrow 3$ for single-particle inclusive spectra).

The general conclusions of the scheme are well known. Those are the Regge behaviour of elastic scattering amplitude, the logarithmical increase of the mean multiplicity, scaling and plateau in rapidity distributions, short--range correlations, etc.

Strictly speaking all those predictions are valid at extremely high energies where eqs. (14), (16) can be used, calculations are simpler and the theorist's life is not questioned by experimentalists.

To complete the picture I start from "asymptotical results" and then move to the realistic models, to the role of conservation laws, etc.

The multiperipheral dynamics of t-channel iterations of low-energy interactions produces the elastic shadow scattering described by the reggeon exchange. Replacing the multiperipheral ladder by the reggeon one can use all knowledge of the reggeon properties which is available from two- and quasitwo-particle processes. It is well known[45] that the inclusive spectra in the fragmentation region for the reaction $AB \to C + X$ are described by the formula

$$\frac{d\sigma^{C}_{AB}}{dy} \sim g_B V_{A\bar{C}}(y) \exp[(\alpha(0)-1)Y] \tag{18}$$

(y is the rapidity, $Y \sim \ln s$). The limiting fragmentation follows from (18) at $\alpha(0)=1$:

$$\frac{d\sigma^{C}_{AB}}{dy} \sim g_B V_{A\bar{C}}(y) + O(s^{-1/2}) \tag{19}$$

up to the terms of the order of $s^{-1/2}$.

Pionization region is characterized by:

$$\frac{d\sigma^{C}_{AB}}{dy} \sim g_A g_B V_{\bar{C}} \exp[(\alpha(0)-1)Y], \tag{20}$$

i.e., by the rapidity plateau for $\alpha(0)=1$:

$$\frac{d\sigma^{C}_{AB}}{dy} \sim g_A g_B V_{\bar{C}} + O(s^{-1/4}) + O(s^{-1/2}) \tag{21}$$

up to the terms of the order of $O(s^{-1/4})$ due to non-leading trajectories and of the order of $O(s^{-1/2})$ due to the kinematical bounds[52]. The former terms are positive if the P'-residue is positive as it follows from the behaviour of total cross sections but they could become negative if the cluster production is taken into account[93]. The kinematical terms are always negative.

Let me note that the rapidity plateau is widely used in parton models where a hadron develops the parton ladder with the energy of each subsequent parton being $\sim \lambda = Const$ times smaller than the energy of the preceding one.

From eq. (21) one gets the logarithmical increase of mean multiplicity (for $\alpha(0)=1$):

$$\langle n \rangle = \frac{1}{\sigma}\int \frac{d\sigma}{dy} dy = a \cdot Y + b. \tag{22}$$

Two-particle correlations are given by

$$C_2(y_1, y_2) = \frac{1}{\sigma}\cdot\frac{d^2\sigma}{dy_1 dy_2} - \frac{1}{\sigma^2}\frac{d\sigma}{dy_1}\frac{d\sigma}{dy_2} \sim e^{-\beta|y_1-y_2|} \tag{23}$$

where $\beta = 1-\alpha_f(0)$, $\alpha_f(0)$ are the Regge-trajectories closest to Pomeron ($\beta = 0{,}5$ if $\alpha_f(0) = 0{,}5$, i.e. there are short-range correlations and β is small if the Regge-cuts close to Pomeron are important, i.e. there is no short-range ordering).

The experimental data about total cross sections initiated the reggeon scheme with Pomeron lying above one[46] in which the different energy behaviour appears for different energy intervals. Since just experiment created this scheme I consider its predictions concerning multiple production processes only in the region of energies now available. Its main results are:

1. Total cross sections increase with energy like

$$\sigma_{tot} \sim e^{\Delta Y} \approx 1 + \Delta Y. \tag{24}$$

It reminds of the logarithmical law because the value of Δ is small ($\Delta \sim 0.06 \div 0.08$[47]).

2. The inclusive distribution develops a plateau in the central region with

$$\frac{1}{\sigma}\frac{d\sigma}{dy}\Big|_{y=0} \sim Const + O(?), \tag{25}$$

i.e., scaling is valid for the function $\frac{dN}{dy}=\frac{1}{\sigma}\frac{d\sigma}{dy}$ (but not for $d\sigma/dy$) and the mean multiplicity

$$\langle n\rangle \sim a Y + b \qquad (26)$$

increases logarithmically.

The t -channel bootstrapping of M -models suffers of the problems of S-channel unitarity i.e. the usual question to all of them is how the elastic (absorptive corrections) and inelastic (multiple ladder creation) rescattering influences the final states. This is the so-called Regge-cut problem. Another question is how the Pomeron is renormalized. Both of them are closely connected with the problems of final state interaction.

Self-consistency of the scheme and its asymptotical predictions have been mainly investigated (see, for example, /48/). The AGK cut rules /49/ for inclusive distributions are widely used. Simple (but may be simplified) prescriptions for calculation of rescattering effects in the pionization region can be derived from eikonal approximation /50/ where the number of exchanged reggeons (ladders) is fixed by the elastic scattering phase. (The criterium of its applicability is the presence of well separated leading particles).

The qualitative effects of rescattering are the increase of the dispersion of multiplicity distribution (in comparison with single-ladder results), the growth of the inclusive spectra in the central region, the long-range correlations, etc. In particular, the mean multiplicity $\langle n\rangle$, the dispersion of the multiplicity distribution D_n , the correlation function f_2 , and the normalized two-particle correlation function $R(p_1,p_2)$ are modified in eikonal model when compared with the single-ladder values $\langle\tilde n\rangle$, $\tilde D_n$, $\tilde f_2$:

$$\langle n\rangle = \langle m\rangle\cdot\langle\tilde n\rangle \qquad (27)$$

$$D_n^2 = \langle m\rangle\cdot\tilde D_n^2 + \langle\tilde n\rangle^2\cdot D_m^2 \qquad (28)$$

$$f_2 = \langle m\rangle\cdot\tilde f_2 + \langle\tilde n\rangle^2\cdot D_m^2 \qquad (29)$$

$$R(p_1,p_2) = \frac{1}{\langle m\rangle}\cdot\tilde R(p_1,p_2) + \frac{1}{\langle m\rangle^2}\cdot D_m^2 \qquad (30)$$

where $\langle m\rangle$ and D_m are the mean number of inelastic rescattering processes and the dispersion of its distribution. Such corrections can help to fit experimental data starting from simplest Poisson distribution for a single ladder /5/ and to account for long-range correlations /57/ which occur due to averaging over different possibilities. This is a typical feature of all many-component models and of those cluster models where one has to average different processes. One can diminish this effect by choosing the processes belonging mainly to the same class (for example, the semi-inclusive processes /101/).

It is well known that reggeon cuts make negative contribution to the total cross section, i.e., the interference of different graphs plays an important role. In particular, the rescattering graph shown in Fig. 4 has properties similar to the ones of usual multiperipheral

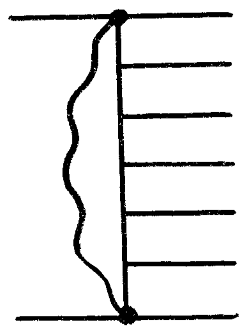

Fig. 4.
The rescattering process .

ladder and, therefore, interferes with it. One can try to take into account this interference just in the framework of the multiperipheral equation (14). The simplest model /53/ predicts that due to the interference the coefficient in front of the integral term (15) should be diminished approximately by σ_{tot}/σ_{in} times. In that case the rescattering processes should not be considered as contributing to the term $\bar{\sigma}$. This again reminds the many-component models where the contributions of different processes are determined from experimental data[54].

The problem of contributions of different processes is closely related to the nature of exchanges and of blobs in multiperipheral graphs. The nature of t-channel exchange (quantum numbers) can be checked in reactions where t is close to the physical pole ($p \to \pi$ or $p \to K$, etc.)[55a] or by studying the rapidity gaps and cherge transfer[55b].

The nature of blobs of multiperipheral graphs is important for understanding the mechanisms of multiple production and influences the correlation parameters of the processes. There exist the schemes with the exchange and the production of the whole set of resonances[56,57] as well as the schemes with pion exchange and the production of resonances[58–60] or, in addition, of fireballs and elastic diffraction of virtual particles[43,61,62] without which the pion exchange seems to be inadequate[43]. The former and the latter versions should differ in correlations.

The qualitative estimetes were performed in cluster models[63–68]. The plateau in the rapidity distribution of clusters is usually assumed and their decay reminds the decay of resonances (with a δ -symbol in multiplicity distribution) or that of fireballs (Poisson-like) . The energy and momentum correlation was incorporated in an approximate way. The main conclusion is that such a model is able to fit experimental data if clusters decay on an average in 3–4 particles.

However the influence of energy-momentum conservation is rather strong at present energies[57,91]. In particulat , it can noticeably change AGK-rules and the form of inclusive spectra. Therefore all preasymptotic formulae should be used cantiously.

Much more reliable and complete calculations with the proper treatment of conservation laws have been performed for multiperipheral cluster model which considers both the resonances and the fireballs[43,62, 76–88]. The Monte-Carlo computer program is used. This is the only model which is able to provide the complete exclusive information about available channels of hadron reactions. It can be considered as "the theoretical bubble chamber" providing the whole set of parameters of all particles including neutrals. It has been successfully compared with experimental data at 40,70 and 200 Gev.

V. Constituent Approach

The multiple production models which try to explain these processes by considering the internal (quark) structure of particles are especially appealing. The interrelation with deep-inelastic lepton-proton processes[69,70] is easily established. These models are still not so well developed as multiperipheral or statistical ones and provide less quantitative results. However they pretend to reveal the internal mechanisms underlying multiple production processes. These models differ mainly by the role played by gluons in production reactions.

The simplest of them is the additive quark model[71,72] which does not take gluons into account. It is assumed[73] that the multiple production process can be described by the graph shown in Fig.5. Such a model explains a number

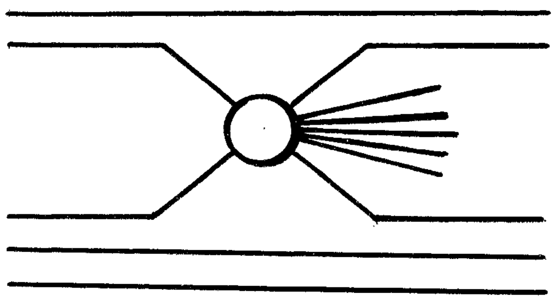

Fig. 5.
The quark graph of the multiple production process.

of typical features of multiple production, in particular, the KNO-scaling[75] (even if there is no Feynman scaling) and predicts some interesting peculiarities. The decisive predictions stem from the fact that the symmetry (forward-backward) system of secondary particles coincides with the c.m. of two interacting quarks which is not the same, on the average, as the c.m. of colliding hadrons for πN and KN processes. Experiment supports the conclusion about the quark-quark symmetry system (see refs./74,76/) however the analysis of the asymmetry of individual πN -events shows some discrepancy/81/.

This model was used to calculate the relative yields of different particles/77-80/ with the assumptions of SU(6) symmetry and of the statistically independent production and redistribution of quarks. Suppressing the production of strange quarks (by the factor of ~ 0.5 compared to usual quarks) it was possible to explain the observed relative abundance of particles of different kind, its energy dependence and its magnitude at large transverse momenta.

There exists an alternative approach/63,82/, which relates the pionization components to the gluon-gluon interaction. All the valence quarks remain spectators and go through the interaction region to produce the leading particles with the flat rapidity spectrum in non-diffractive inelastic processes. Such a spectrum is consistent with the steeply decreasing spectrum of quarks, typical of deep-inelastic lepton-proton processes.

A slightly different role is prescribed to gluons if one assumes/83/ that during the collision they are transformed into $q\bar{q}$ -pairs which enlarge the quark sea. Afterwards the quarks from the sea are redistributed and from the final particles like in the additive-quark model/77/. The first attempt of the global quantitative description of multiple production has been made within such a quark model/83/ with the Monte-Carlo simulation.

The most attractive feature/74,82,83/ of quark models is that they show that the unique quark distribution functions in the proton can explain the main features of electromagnetic, weak and strong interactions. Some people argue/84/ that the strong quark-quark interaction with the low transferred momentum can also explain the universal jet structure of multiple production processes at high energies.

VI. Comparison with Experiment

Even though each group of the models considered pretends to describe experimental data, however the most extensive quantitative studies have been performed for the hydrodynamical models with the state equation $p \approx 0.2\,\varepsilon$ /13,14,20/ and for the multiperipheral cluster model/43,62,85,86/.

Table I.*)

Experimentally available data	H-models	M-models
I. Total cross sections	–	–
II. Multiplicity		
1) energy dependence of $\langle n \rangle$	+	+
2) distribution and its moments	+	+(?)
3) KNO-scaling	+(?)	+(?)
4) $n_{\pi^0} = F(n_{ch})$	+(?)	+
5) composition	+	–(?)
III. The rapidity spectra		
1) pionization region	+	+(?)
2) fragmentation region	–	+
3) energy dependence	+	+(?)
4) semi-inclusive distribution	–	+
IV. p_T -spectra		
1) low	+( )	+
2) large	+(?)	+(?)
3) semi-inclusive distributions	–	+
V. The pair-mass and transferred momenta distributions	–	+(?)
VI. Correlations		
1) dependence p_T on p_L	+	–
2) azimuthal	–	+
3) two-particle rapidity correlations	–	+
4) many-particle (rapidity intervals)	–	+
5) charge transfer	–	+(?)
VII. Inelastic diffraction	–	+

*) The plus sign means that the good quantitative agreement is claimed by the model. The minus sign is used in the following cases:
1. the theory is unable to predict this characteristics,
2. the results are unsatisfactory,
3. no calculations were performed.
The additional arguments in favour of the plus sign ( ) or against the obtained results (?) are marked in brackets.

Therefore I have chosen these two models which differ strongly in their assumption and methods to compare them and to show how many experimental distributions are described by them (see Table I). The main conlcusion that follows at first glance from the Table is that up to ISR energies the inclusive distributions do not separate definitely the two models. (The latest data about the pionization spectrum in ISR region can be more conclusive). I will discuss mainly those features which can not be easily explained or are most sensitive to the mechanisms of multiple production. I omit many successes of the theoretical schemes.

1. Total Cross Sections

This is the simplest and most precisely known quantity but it is the one which always enforces the theory to change its parameters. H-models do not pretend to calculate total cross sections. M-models use experimental data about the energy behaviour of total cross sections to get some knowledge about the leading trajectory (and about the ones nearest to it) and to choose some parameters of multiple production models.

For example, the energy behaviour (24) in preasymptotical region is determined in reggeon scheme by the parameter Δ the value of which 0.06-0.08 is chosen according to ISR data. The asymptotical behaviour is governed by the law $\ln^{\eta} s$ where η is not definitely established but is rather small[47].

The properties of ρ and ρ' -trajectories help in choosing the parameters of the multiperipheral cluster model[43,85].

Eikonal models provide a variety of asymptotical regimes according to the nature of exchanged particles[88] from the constancy $\sigma \sim const$ to the Froissart behaviour ($\sigma \sim \ln^2 s$).

C -models predict only the ratios of the cross sections for different initial particles. For example, the additive quark model predicts $\sigma'_{pp}/\sigma'_{\pi p} \approx 3/2$ /72/ (the experimental value is $\sim 5/3$).

In conclusion, experiment but not the theory is leading here.

2. Inclusive Single-Particle Spectra

Let me show in the beginning how nicely the rapidity distributions can be fitted in controversial models (see Fig. 6a for H-models and Fig. 6b for M-models).

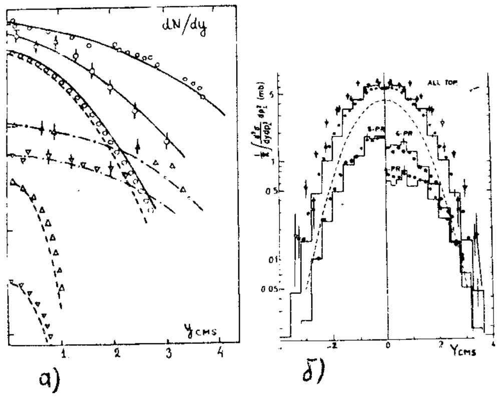

Fig. 6.
The rapidity distributions
a) H-model[13] (points are experimental ones, curves are theoretical ones)
b) M-model[43] (dots are the theoretical results).

Now I am coming to an interesting problem which is imposed on the theory by experimental results[89] about the large increase of inclusive spectra at $x \simeq 0$ in the energy region from $\sqrt{s}=23$ to 63 GeV (about 40% for pions). It is demonstrated by Fig.2 in /90/.

For H-models where scaling is violated ($\langle n\rangle \sim s^{1/4}$) the growth is rather large even though it does not seem very unnatural ($\frac{s^{1/4}}{\sqrt{\ln s}}$ changes just by 40%). Statistical formulae similar to (3) explained rather well the yields of secondary particles $\pi, K, \bar{p}$ /24,25,28/, ρ /28/, d, He^3 /24,25/. They predicted the larger increase of the heavier particle production[24,25] (for example, $\langle n_{\bar{p}}\rangle / \langle n_{\pi}\rangle \sim \langle n_{\pi}\rangle$ that should be compared with ISR data[89] $1,74/1,4 \approx 1,4$).

The increase of the pionization component at $X \simeq 0$ imposes extremely severe restrictions on all attempts to revive F-models in this region.

In the reggeon interpretation of M-models one can attempt to use the formulae (21), (25)

$$\frac{1}{\sigma}\frac{d\sigma}{dy}\Big|_{y=0} \sim \begin{cases} 1 - \dfrac{d}{s^{1/4}} & \text{(31a)} \\ 1 - \dfrac{f}{s^{1/2}} & \text{(31b)} \end{cases}$$

depending on whether one attributes the main role to cluster density increase[93] or to kinematical effects[52]. In both the cases the correction terms seem to be too high ($d \approx 2$, $f \approx 9$) to be naturally accepted. The break of the curves in Ferbel plot is easily seen.

A possible explanation of this effect both by the increase of the number of multiperipheral ladders and by the strong restrictions imposed by conservation laws (of the type[91]) would mean that the simplest reggeon approach fails and one should use large corrections. The growth of the heavy particle production imposes some problems on the multiplicative production of ladders which reduces the increase of heavy particle contribution because the whole process becomes to split into processes with lower energies.

In cluster models with rather wide distribution of cluster masses (i.e., different from resonances) the increase of inclusive spectra can appear if scaling is violated within the cluster, i.e., the product of the mean multiplicity within the cluster K on its production cross section increases[44]. Sometimes the nucleon-antinucleon clusters are blamed for such an increase of inclusive spectra[92]. There are also some phenomenological proposals of new scalings for semi-inclusive[87a] and inclusive [87b] spectra leading to some increase of $\frac{1}{\sigma}\frac{d\sigma}{d^3p}$ (the variables are $\frac{y}{Y}$, $\langle n\rangle x$ or $(p_L/\langle p_L\rangle)_n$).

The experiment shows that neither of the theoretical conditions for early scaling is valid. The conditions are usually formulated as the requirements for some groups of particles to have exotic quantum numbers ($AB, A\bar{C}$ or $AB\bar{C}$) or for the system $A\pi\bar{C}$ to be non-exotic[93].

The transverse momentum distribution is

$$\frac{dN}{dp_\perp^2} \sim \exp\left[-\mu_T/T\right] \qquad (32)$$

where $\mu_T = \sqrt{p_T^2 + m^2}$, describes well with one and the same temperature T experimental data on $\pi, K, \bar{p}$ [24,25,28], D, ψ [27] in H-models for which such a behaviour is quite natural (see eq. (3)). One can notice even a slight difference from Boltzmann distribution (32) due to more correct Bose-Einstein statistics[28]. It is important also for the theoretical calculations of the density of states in relativistic ideal gas in application to H-models[94]. The mean transverse momentum is limited by the temperature T but can increase slightly $p_T \sim s^{\gamma}$ $(\gamma = \frac{1}{12} \div \frac{1}{14})$ at still higher energies[6,29].

At present the field theory and graph (multiperipheral) models can not explain such a behaviour of transverse momenta without additional ad hoc form factors. Nevertheless, the form factors chosen reasonably could supply us with the fits of experiment[43,85] which do not look worse than the previous ones.

In the large transverse momentum region the most popular ones are C-models (see rapporteur's talk of Darriulat). But H-models also pretend to explain the spectrum behaviour in p_T [28,30,31] its energy dependence and the increasing role of heavier particles[28] by the leakage of particles at the earlier stage of the system development. Some additional information about this stage could be obtained from spectra of photons and leptons[95].

The simple resonance ladder in M-models contradicts the experiment because it predicts the decrease of associated multiplicity at higher p_T [56]. Therefore, if one wants to preserve the multiperipheral approach one should consider creation of heavier clusters[43,96] in the multiperipheral graph. For understanding the mechanisms of multiple production it is important to know how many resonances are produced on an average in each event. However, experimental data are not precise enough (for example the percentage of pions from resonance decay is estimated from 20 to 70% [97-100,81]). The experiments in which the leptons from the resonance decay are detected could, in principle, clear up the situation. The qualitative predicts of the models are as follows. There are many resonances in multiperipheral resonance ladders[56,57], they produce a pronounced effect in multiperipheral fireball model[43,85] but few resonances are produced in some versions of quark model[80b].

3. Correlations and Clusters

The separation of dynamical correlations from purely kinematical ones (due to the energy-momentum conservation) is a difficult task. The widely used functions $C(y_1,y_2)$ and $R(y_1,y_2)$ whose maxima at $X=0$ support the short-range order models with cluster production are not very informative. The semi-inclusive correlations C_n and R_n start from different levels for each n and interfere strongly when combined into inclusive functions C and R. Nevertheless, taking into account these effects it is possible to show that the main conclusion about short-range ordering persists[101,102]. Approximately, $2\div 3$ charged particles are attributed to each cluster from such a method in independent cluster emission models[68,103,104]. The similar values are obtained from the rapidity gap distribution[105,106]. It is easy to show that for independent emission of clusters decaying into K particles and distributed along the rapidity axis with the constant density ρ the rapidity gaps Δy follow the laws[106,107]:

$$dN/dy \sim exp[-\rho K \Delta y] \text{ at small } \Delta y, \quad (33)$$

$$dN/dy \sim exp[-\rho\, \Delta y] \text{ at large } \Delta y. \quad (34)$$

Formulae (33), (34) compared with the experimental curves give the above conclusions. However, there was a criticism of such estimations and twice as large values of K were obtained from the fluctuation analysis[108].

Inclusive distributions of rapidity gaps are not very sensitive to the mechanism of multiple production[62,109] and are strongly correlated with the mean multiplicity. The more effective way is to investigate the semiinclusive distributions of rapidity intervals[62,107,109,110] which are determined as intervals between two particles which contain some other particles inside the interval i.e.,

$$\Delta y_{i,K} = y_{i+K+1} - y_i \quad (35)$$

(at $K=0$; $\Delta y_{i,0} \equiv \Delta y$), where i are numbers of particles along the rapidity axis and K is the number of particles inside the interval.

These distributions have maxima moving to lower values of interval length when the role of clusters increases [107] (Fig. 7). The calculations have shown that the most sensitive ones are the distributions with K of the order of $n/2$ (n is the multiplicity of an event). The comparison with experiment[62,110,111] was made and these distributions helped to distinguish between the two versions of the multicluster model both of which explained successfully other experimental data.

Let me stress that when studying intervals $\Delta y_{i,K}$ we learn something about many-particle correlations and this way is much simpler than the many-dimensional generalization of functions C and R.

The correlations between the produced clusters and exchanged links could be studied by the rapidity interval method joined with the charge transfer[112,113]. Connection between correlation functions for the processes initiated by different projectiles can be sometimes established using isotopic invariance[114]. The function C can be revived if considered as a

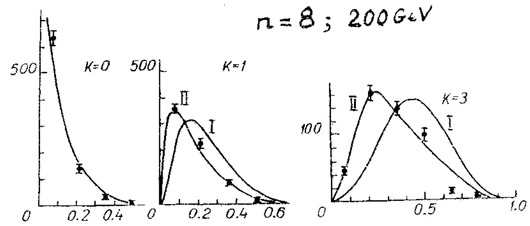

Fig. 7.

The rapidity interval distributions[110].
I - independent particle production; II - independent cluster production.

function of mass of pair of particles (see Fig. in[68]).

In conclusion , we should deal with the clusterization phenomenon. If there is anything dynamical besides resonances in the notion of clusters it should be further studied, I'd like to argue in favour of the point of view that some heavier correlated groups of pions are created: 1. the correlated groups contain on an average at least 2÷3 charged particles (for resonances the value 2 is an absolute limit and the value 1, 3÷1.5 is the most probable one), 2. the effective mass of the group varies from 1.5 to 3 GeV which is higher than all prominent boson resonance masses, 3. the charged multiplicity of the cluster decay K increases with n for $n > \langle n \rangle$ i.e., the multiplicity distribution for a cluster is not described by δ - function[101] (fig. 8), 4. the slope of the logarithmical increase of the mean multiplicity is too small for the schemes with resonance production, 5. the strong increase of inclusive production of K and $\bar{p}$ at ISR-energies favours cluster interpretation.

Qualitatively this point of view is supported also by the scaling violation at $x = 0$, the belated increase of total cross sections, the high p_T behaviour.

Now I'd like to make the general comment on the comparison of models with experiment. At

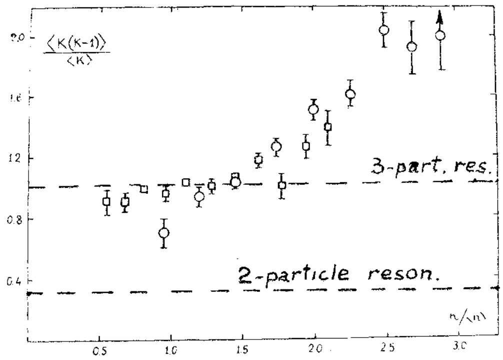

Fig. 8.

The value of $[\langle K(K-1)\rangle / \langle K \rangle]_n$ as a function of $n/\langle n \rangle$ at energies $\sqrt{s}$ =23÷63 GeV[102]. The levels for the decay of 2- and 3-particle resonances are shown (ρ -like and ω -like ones).

present we witness the "multiple model production". Any serious model should pass through the complete quantitative comparison with experiment. It implies the huge amount of numerical Monte-Carlo calculations[43,62,83,85,86,115] with some analytical estimates. Sometimes such a widespread comparison is decisive because a model can reproduce some data and fails at other points. It was demonstrated in analysis of multiperipheral cluster models[43,62,85,86,115] and of quark models[83]. We should also propose the criteria to kill models.

Here I tried to discuss those experimental facts and theoretical methods of analysis which discriminate different models and help to choose the most promising objects for the further investigation.

VII. Space-Time Picture

The space-time description of the process could be useful for studying the multiple production. The naive geometrical consideration leads to the Lorentz-contracted disk and to impact larger multiplicities at smaller parameter b . Vice versa, for the simplest multiperipheral ladder one gets the larger multiplicity for the longer ladder.

It is possible to distinguish two pictures in the experiment.

The effective transverse distance ($b_{eff} \sim 1\,fm$) typical of the whole set of inelastic processes is determined from the elastic differential cross sections applying the unitarity condition (fig.9). Most peripheral ones are the diffraction dissociation processes /116-119/.

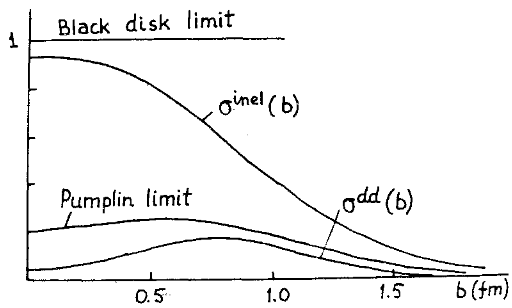

Fig. 9.

The impact parameter structure of total cross section and of inelastic diffraction processes σ_{dd}.

It is possible to estimate the lower limit of the values of b_{eff} for any exclusive channel according to the formula/120-122/:

$$\langle b^2 \rangle = \frac{\langle \sum_i \left(x_i^2 - \frac{k_i^2}{2p^2}\right) \rangle^2}{\langle \sum_{i,j} x_i x_j \vec{k}_i \vec{k}_j \rangle} \equiv b_L^2 \qquad (36)$$

where K_i, p - are the momenta of produced and colliding particles.

The results obtained are: 1) b_L decreases 3÷4 times when the multiplicity increases from 4 to 9, i.e., the multiplicity is higher for central interactions, 2) at fixed multiplicity b slowly increases with energy, 3) b_L is larger for inelastic diffraction, 4) b_L is smaller for the strangeness or baryon number exchange processes.

Therefore in such interpretation these result supports the naive geometrical picture rather than the multiperipheral Brownian motion in the transverse plane. It may be related to the fact that multiperipheral logarithms are in general much smaller than residues' contributions. The refinement of eq. (36) is suggested in/122/.

The problem of understanding the effective longitudinal distances is more complicated. When dealing with H-models one uses explicitly a geometrical picture of Lorentz-contracted and expanding volume/1-3,123/. Contracted volume appears also in cylindrical phase space picture (uncorrelated jets)/124/.

At the same time effective longitudinal size and time duration determined by dependence on four momentum squared of incoming particle/125/ appears to be large for electroproduction amplitude/126/, $Z_{eff} \sim \frac{E}{m^2}$. Long time interaction can be realized in multiperipheral parton picture with interacting slow partons. In this picture the time of formation of parton ladder /125b,127a/ is of the order of $\frac{E}{m^2}$, whereas at a fixed moment hadron consists of the outer shell, whose form is close to the sphere $\sim \frac{1}{m}$ (slow parton) and internal contracted shells (fast partons), the transversal size being of the order of $\sqrt{R^2 + \alpha' \ln E}$ at large E's .

The similar picture of long time formation of a "dressed state" was studied earlier in electrodynamics/130/ and it was exploited for interpretation of hadron-nucleus interactions/131,132/.

Let me note that there exists a proposal to consider a hadron as a parton state of length $\sim \frac{E}{m^2}$ /127b/.

A method of studying the space-time region is proposed and used in the experiment/128/. It exploits the second order interference effects (similar to the Hunberry-Brown, Twiss method in astronomy). The experimental results/129/ $R \sim 1$ fm and $c\tau \sim (0.4÷0.7)$ fm do not contradict what was expected. However the interpretation of the value of τ and restrictions imposed by the smallness of the relative momentum of two detected pions need further study.

In conclusion, the problem of the space-time description is far from being solved and must be discussed. Our main hope is to use the hadron-nucleus collisions to clear it up[131,132].

VIII. Extremely High Energies

What can we say about mechanisms of multiple production at still higher energies?

The region of $10^{14} \div 10^{15}$ eV is often thought of as a region where some new phenomena may appear. Which facts from the cosmic ray studies are known?

1. Total cross sections increase slowly (if at all) with energy (Fig. 10).

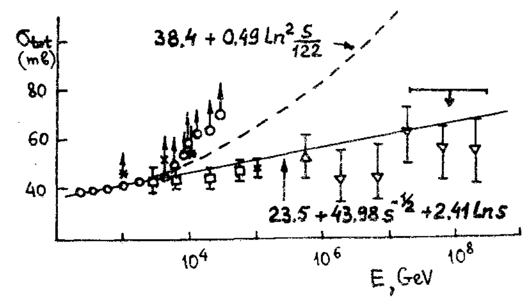

Fig. 10.
The energy dependence of total cross sections at very high energies.

2. The mean multiplicity increases, probably, faster than logarithmically (Fig. 11).

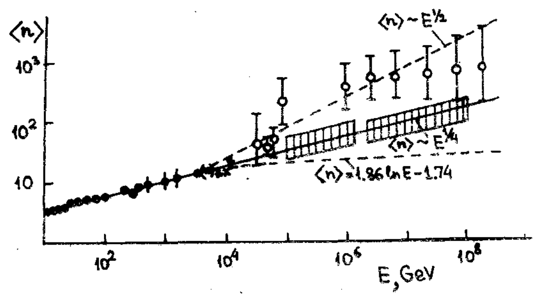

Fig. 11.
The energy behaviour of the mean multiplicity of charged secondaries.

Let me note that at present there is no theoretical scheme which predicts the logarithmic behaviour of total cross sections (but not $\sim \ln^2 s$) and the strong power increase of mean multiplicity (with the high enough power).

3. Scaling for $\frac{E}{\sigma}\frac{d^3\sigma}{d^3p}$ is, probably, violated in the pionization region[133]. As the calculation shows[133b] the data of the experiment "Pamir" in the energy region $10 \div 10^3$ TeV could be fitted best of all if the inclusive distribution $E\frac{d^3N}{d^3p}$ at small $|x|$ increases while it decreases in the fragmentation region. It coincides with the trends observed at ISR.

4. At energies about 10^{14} eV the absorption of the hadronic component of air showers starts decreasing[134-137]. If it is interpreted as the creation of a new highly penetrating component than it should contribute about 25% of hadronic component at energies above 100 TeV.

5. The energy shared in electron-photon component increases compared with the energy of hadronic component in the center of air shower from 0.8 to ~ 1.5 in the energy interval 40-300 TeV. These results were interpreted[134-137] as a consequence of production of some new particles with their subsequent decay into electrons and photons or as a possible associative production of new particles with leptons and photons.

6. There exist some exotic events. The most interesting ones are the events with the production of the large number of particles in the narrow rapidity interval which have been interpreted as the production of very heavy clusters with masses up to 25 GeV/c^2 or as very large p_T -events[138].

I would mention that the clusters with masses 3-4 GeV/c^2 were discussed in cosmic ray physics long ago [139].

And, finally, we may hope that the energy region above 10^{14} eV will persuade us to change our opinion about mechanisms of multiparticle production. The colliding beams 1×1 TeV^2 would just enter into this region.

IX. Conclusions and Perspectives

The experimental data about the increase of total and inclusive cross sections, the behaviour of the mean multiplicity and correlations at high energies provide a very interesting clue for further development of multiple production theory. Thus I hope that the next Conference will be more definite about the validity of some models.

Now I would like to discuss how the multiple production studies are connected with other problems arising in the neighbouring fields of particle physics.

Surely the interesting relationship is provided by C-models because they are intimately connected with the internal structure of particles. It would be valuable to understand which features of the internal structure are related to the cluster production. Probably, the clusters could result from the non-linear theory of particles and their interactions in a way similar to the transformation of two quantum solitons in n solitons (or two bags into n bags[140]). The problem of kinetics of such solitons is related to the speculations about the so-called young particles[130].

Dynamical description in terms of non-linear Lagrangians is connected with the transport theory and further with the statistical and hydrodynamical approaches. As we have seen one can derive here the form of inclusive spectra and therefore find some correspondence with the reggeon approach to inclusive processes.

By itself the problem of the connection between statistical and dynamical approaches to multiparticle production is a part of more general question of how dynamics transforms in statistics[141]. Surely the observation of statistical behaviour in inelastic processes would be invaluable for particle models.

Non-linear effects can appear in a way similar to that of superconductivity. The state equation of hadronic matter can be very complicated. For instance, such state equations which give rise to phase transitions in hadronic matter, to its superfluid properties, etc., were already exploited. The problem of state equation of hadronic matter is important not only for understanding the hadron-hadron and hadron-nucleus collisions at high energies but it plays a noticeable role in cosmological studies.

In conclusion I would like to say the situation with our understanding of multiparticle production is far from being clear. The capital letters of the reviewed models form the phrase:

"Multiple Production Has Curiour Features".

Still much time is needed to make all of them clear and predictable.

Acknowledgements

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