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THE TWO-CENTER MODEL AND THE HYDRODYNAMICAL THEORY OF THE MULTIPLE PRODUCTION OF PARTICLES

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It is pointed out that when there are fluctuations of the initial volume or the final temperature the hydrodynamical theory of collisions of high-energy particles can lead to kinematics similar (but not identical) to that predicted by the two-center model.

RECENTLY a large number of papers have appeared (cf., e.g., references 1–3) giving analyses of showers registered in photographic emulsions and showing a sharply marked two-cone structure in the center-of-mass system. The kinematics of such showers can be described approximately by means of the following model: after the collision two quasi-independent systems ("fire balls") are formed, which then disintegrate isotropically in their own coordinate systems into real particles. It is well known, however, that the hydrodynamical theory of the multiple production of particles[4] is based on the existence of a single system at the instant of the collision. Therefore the question can arise of the necessity of placing these two models in opposition to each other. Without entering here into the question of the relative statistical reliability of the conclusion that two centers exist in a collision,* we would like to point out that in principle the hydrodynamical theory can lead to a kinematics of collisions which is close to that corresponding to the two-center model. The main argument against this assertion has been the difference between the angular distributions of the secondary particles as observed experimentally in these particular showers and as theoretically predicted by the hydrodynamical theory. Whereas it was previously supposed that in the center-of-mass system the theoretical maximum of the angular distribution lies in the range of angles around $\pi/2$ (if one plots as abscissa the quantity $\eta = -\ln \tan \vartheta$), experimentally one sometimes observes a minimum in this range of angles, which has a natural explanation in the two-center model. Figures 1 and 2 show as examples the angular distributions of two showers. One of them (Fig. 1) is characterized by a single maximum and is well described by the hydrodynamical theory; the other has a "two-hump" structure which corresponds approximately to the kinematics of the two-center model.

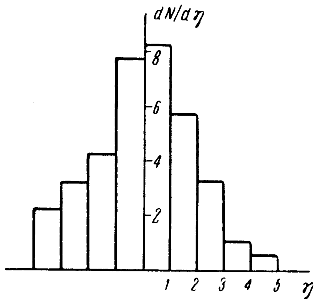

FIG. 1. Angular distribution of secondary particles in a case with a single maximum.[5] Type of interaction $1+0+37\alpha$, $\eta = -\ln \tan \vartheta$.

In the present paper we put forward the proposition that in some cases the collision kinematics predicted by the hydrodynamical theory can be close to such a "two-hump" distribution, and consequently it can simulate the kinematics of two independent centers. We begin our argument with the statement that some such "two-hump" character always exists, but cannot in practice manifest itself. Our arguments will be based on the consideration of the simple wave in the hydrodynamical solution of the problem of the separation of particles, which has not previously been taken into account in the analysis of "two-humped" showers. In fact, the particles that arise in the disintegration of the simple wave (cf., references 6, 7) have the following properties:

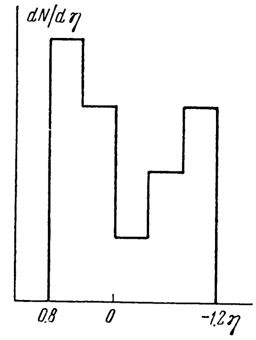

FIG. 2. Angular distribution of secondary particles in a case with two maxima.[1] Type of interaction 0 + 13p.

*The showers that give evidence of the existence of two centers are as a rule obtained as the result of a very severe selection.

with neglect of the thermal motion and for a definite primary energy the angular distribution of these particles is given by a δ function. Therefore, strictly speaking, there must be δ functions at both ends of angular distributions, and consequently the curve should theoretically have maxima at the ends and a drop in the middle. Under ordinary conditions, however, the influence of the δ-function term on the distribution is very small. In fact, the fraction Δ of the particles in the simple wave is given by the ratio

$$\Delta = T_f / 2T_0, \tag{1}$$

where T_0 is the initial and T_f the final temperature. Assuming that $T_f = \mu c^2$ (μ is the mass of the π meson),[8,9] and calculating T_0 for the initial uncompressed volume taken to be a sphere of radius $\hbar/\mu c$, we can find that there is less than one particle in each of the two simple waves, and naturally this has little effect on the total distribution. Figure 3a shows the angular distribution of the secondary particles for primary energy $E_0 = 10^{12}$ ev with the simple waves included. Here, however, the angular distribution of the secondary particles in the simple wave is represented not as a δ function, but spread out so as to take into account the thermal motion. We have approximated its effect by a Gaussian curve with $T_f = \mu c^2$.

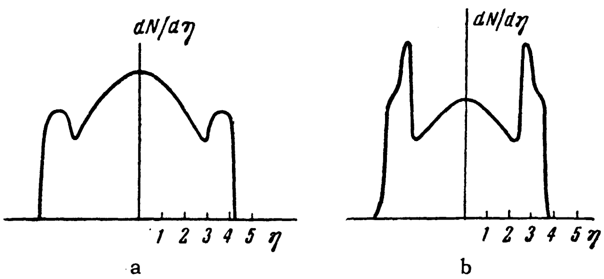

FIG. 3. Theoretical angular distribution for nucleon-nucleon interaction with $E_0 = 10^{12}$ ev: a – interaction radius $\hbar/\mu c$; b – interaction radius $2\hbar/\mu c$.

It follows from Eq. (1) that Δ depends essentially on the ratio T_f/T_0. Therefore we may suppose that to get an explanation of the "two-humped" behavior within the framework of the hydrodynamical theory we should change the value of this ratio. Some physical effects can be named that could in principle lead to an increase of this ratio. For example, it is very likely that the quantity T_f can fluctuate from shower to shower (of course in such a way that we still have $\overline{T}_f = \mu c^2$). Another cause of an increase of this ratio could be a change of the nature of the elementary act (for example, the "degree of peripherality,"[7,10] which brings with it a change of the size of the initial volume*).

Figure 3b shows the angular distribution of the secondary particles for $E_0 = 10^{12}$ ev and a doubled radius of the interaction volume. A still larger part can be played by the simple wave if the experimental indications[11] that there are showers with very small energy losses ($\sim 0.15\ E_0$) are confirmed. Such collisions can be crudely interpreted (although such an interpretation is to a considerable extent arbitrary) as resulting from collisions of "quasi-real" π mesons. In this case there is an even larger increase of the value of Δ. Figures 4a and b show

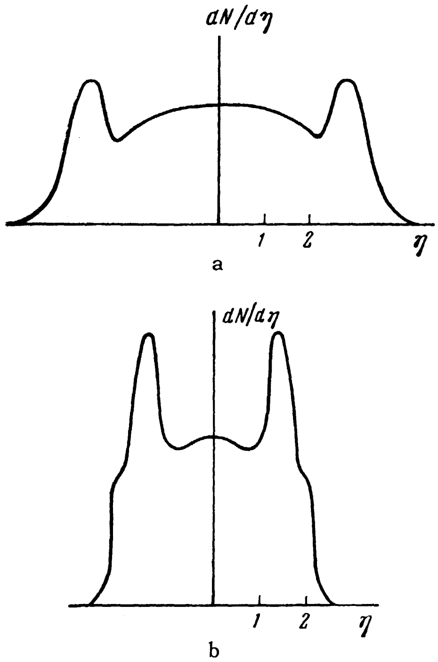

FIG. 4. Theoretical angular distribution for nucleon-nucleon interaction with energy $E_0 = 10^{12}$ ev: a – interaction radius $\hbar/\mu c$; b – interaction radius $2\hbar/\mu c$. The interaction is interpreted as a $\pi\pi$ collision.

angular distributions of the secondary particles produced in collisions of nucleons with energy $E_0 = 10^{12}$ ev. The collisions are interpreted as collisions of two π mesons moving with the same velocities as the nucleons. Furthermore it helps the explanation to note that because of the thermal motion the particles will spread apart isotropically in the coordinate system associated with the simple wave, and this simulates the effect of separate centers.

In conclusion we must state how differences can appear between the two models. First of all, if we do not assume an increase of the volume V_0 with

*In cases in which there is a fluctuation of the decay temperature and $T_f > \mu c^2$ (for the region of the simple wave) the transverse momentum of the particles will be larger than for $T_f = \mu c^2$; besides this, the fraction of K mesons among the secondary particles is increased.

the energy, then already for $E_0 > 10^{13}$ ev the "two-humped" character based on arguments from the hydrodynamical theory must disappear.*

At the present time, however, on the basis of the available experiments one cannot distinguish with certainty between the models based on the assumption of a single system and of two systems. The two models can lead to similar (though not identical) kinematics. The fact that the characteristics of individual, rarely occurring, showers may disagree quantitatively (but not qualitatively) with the curves shown in Figs. 3b and 4b is by no means a refutation of these curves. In fact, each of the "humps" of these curves contains on the average 2 to 4 particles. Furthermore there can be very large fluctuations acting to change these numbers. The problem of the quantitative testing of the present arguments (and also of any other theory describing the "two-humped" showers) can be solved only after thorough statistical analysis of experimental data.

*More exactly, this is true for the "two-humped" character arising from Eq. (1); as has been pointed out by G. A. Milekhin (private communication), if we resort to a more radical revision of the hydrodynamical theory (renouncing the equation of state $p = \varepsilon/3$) the "two-humped" behavior may become much more pronounced.

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