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SOME REMARKS ABOUT FIREBALLS

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In the paper a definition of the fireball is proposed. It has been shown that fireballs fulfilling this definition are produced in very wide energy range up to some tens TeV. Arguments have been presented in favour of the fireball model as a model of pionization.

Proposal of a definition of the fireball

More than ten years ago the fireball model was suggested as a phenomenological description of nucleon-nucleon interaction at cosmic ray energies with multiple production of particles (Cracow group (1958), Cocconi (1958), Niu (1958) — *Cf.* Ref. [1]). Later, it became customary somehow for the physicists to use the term "fireball" not only in cosmic ray investigations, but also in accelerator physics. In the numerous papers that have appeared since the original model had been proposed the term "fireball" has not been used in a unique sence. It thus seems it would be useful to propose a definition of the term "fireball" and to review experimental facts which could be explained by fireballs in this meaning.

At the moment we are proposing a simple tentative definition useful for the interpretation of experimental results, postponing for the time being the discussion about the dynamical nature of the fireball [2].

We will understand by a fireball a group of mesons which have been produced in the high energy interaction of hadrons, in general not resting in the CM-system of the collision. The momentum distribution of these mesons in the rest system of the group corresponds to an isotropic phase space distribution, the average energy of mesons in this system being about 0.5 GeV.

At the time when the fireball model was proposed, with the emulsion technique as the only experimental basis, the bimodal angular distribution in log tan θ coordinates was the main argument for the model. However the bimodal angular distribution cannot always be directly interpreted in terms of emission of fireballs. Therefore the observation of single fireballs and in the case of two fireball emission the demonstration that each group analysed alone, provided they are sufficiently separated in the angular distribution, exhibits fireball

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properties, are now considered to be the main arguments supporting the existence of fireballs.

Accepting the above criteria, of course in an approximate meaning because of the rather poor accuracy of jet measurements, we shall present hereafter a review of the fireball evidence in different energy intervals.

Production of fireballs at different energies and their characteristics

In the energy range 10–100 TeV we have the results of the Japanese-Brazilian group [3]. The angular distributions and the energies of γ-rays, recorded by means of electromagnetic cascade in large emulsion chambers at high mountain altitudes, are measured. The isotropy and the momentum spectrum consistent with the phase space in the rest system of separated groups of π^0 have been reported by the authors.

In the energy range 1–10 TeV the method of nuclear emulsion irradiated during stratospheric balloon flights is used. Here, I refer to a series of papers of the Cracow group (*e. g.* see [1], [4]). The previous results concerning the double maximum angular distribution in log tan θ coordinated have been recently confirmed by Rybicki and Wolter [5] in studies on large blocks of emulsion by means of the method of "beams" of nucleons of the same and known energy produced in the fragmentation process of primary nuclei.

In all events in which the two cones, *i. e.* the forward cone and the backward cone, are well separated and it is possible to analyse the corresponding groups of particles separately, the isotropic emission in the CM system of the group has been found. Also in the case of "asymmetric" jets in which only one cone of particles is observed, isotropic emission has been ascertained (Gierula and Mięsowicz [6]).

The emulsion method at these energies does not enable us to measure the energy of secondary particles, except π^0 in some cases. Therefore there isonly indirect information concerning the momentum distribution of particles in the CM system of the group. This information follows from the transverse momentum p_t-distribution measured for π^0-mesons by Fowler and Perkins [7]. If we accept as the best fit for experimental p_t-distribution the form $\sim p_t \exp(-p_t/p_0)$, it is in rough agreement with the momentum distribution of the phase space type for particles in the rest system of the group (Coghen [8]).

At energies of several hundreds GeV we rely above all on the data obtained by Moscou Group of the Lebedev Institute (*e. g.* see [9]) with the help of the cloud chamber with LiH-target connected with an ionization calorimeter. The apparatus was in operation in a high-mountain laboratory. Meson groups moving in the direction of one of the colliding nucleons are observed after transformation of the angular distribution into the CM-system of the collision, making use of the energy determined in the ionization calorimeter. The angular distribution and the momentum spectrum of the particles, in the CM-system of the whole group, were measured. These distributions appear to be isotropic and consistent with Planck spectrum which we can consider as being in rough agreement with the phase space distribution.

Also at accelerator energies groups of mesons with fireball properties are observed. Investigating the many-body reactions in $\pi\, p$ interactions at 8–16 GeV/c, we observe always in the CM-system of the collision the backward peaking of baryons, even for highest multiplicities. The four momentum transfer distribution between a proton and the group of pions, if corrected for phase space (Białkowski and Sosnowski [10]) is similar to four momentum distribution observed for two-body reaction. It has been shown [11] that at 8 GeV/c $\pi^- p$ collisions producing six- and eight prong stars the whole group of pions exhibits fireball properties. The pions in the rest system of the group are emitted isotropically and with a momentum distribution predicted by the phase space.

For higher energies (*e. g.* at 16 GeV/c) this simple model does not work. The angular distribution of pions in the rest system of the group is anisotropic.

So we can say that at accelerator energies we cannot find the general description of many-body reactions by means of a simple fireball model. Perhaps the experimental difficulties of separating the pionization (see below) process from other ones are responsible for this.

As regards fireball properties other than those included in the fireball definition, one can obtain only rather approximate information about their mass and multiplicity of their production on the basis of the above listed experiments.

The distribution of the fireball mass observed in different experiments is rather broad. The most likely mass taken from different experiments is roughly speaking between 2 and 4 GeV/c^2.

The number of fireballs created in one collisions is usually one at 200–400 GeV and around 1 TeV usually two.

Fireball model as a model of pionization

For several years, or more precisely, since the discovery and its great development of the physics of isobars and resonances, two separate processes of particle production at very high energies have been considered. Namely, the process in which the main fraction of particles is produced, for which the CM-energies of particles are relatively low and their spectrum depends relatively weakly on the primary energy, this is called the pionization process. On the other hand it is possible that also at ultra high energies, nucleons become excited to the isobar state, the decay of which gives also some contribution to particle production. The CM- energy of the particles produced by the latter process is strongly dependent on the primary energy namely, it is simply proportional to the primary CM-energy.

This last process cannot be the main process of particle production at ultra high energies. This would be inconsistent with the observed low mean value of the inelasticity coefficient or with the notion of the leading baryon. This was the reason why the fireball model was introduced. In this model the inelasticity is bound with the free parameter of the model *i. e.* with the $\bar{\gamma}$ Lorentz factor of the fireball in the CM system [1]. Thus the fireball model is a model of pionization. But the very important point is that pionization is anisotropic (*Cf.* Ref. [2]) and this is exactly what is described by moving fireballs.

It seems that the experimental data also at ultra-high energies provide some evidence of isobar production [12]. A small number of mesons can come from their decay, *i. e.* apart from the fireball process. So we accept the general model "pionization + isobar decay" but, we do not see any possibility to describe the observed anisotropy only by izobars.

However, these is a group od data for which it is impossible to say unambiguously whether the observed fireballs really represent a pionization process. Namely very large $\bar{\gamma}$-values are obtained for the interactions at energies 10–1000 TeV registered in emulsion chambers irradiated in mountain laboratories Japanese-Brazilian groups [3] or in the aircraft (Apanašenko *et al.* [13]). If in this type of apparatus we have a preference for recording events with high values of inelasticity, it is impossible in this type of experiment to state that the nucleon after the collision is separated from the fireball. But we must emphasize that using the type of apparatus as reported for these experiments, we have no possibility of recording photons of lower energies coming from typical pionization process. So we do not observe here the pionization because of the unefficiency of the method. Strictly speaking, we cannot say whether or not the pionization exists in these events.

Discussion

All that was said thus far concerned fireballs as defined at the beginning of this note. This type of description appears to be useful and, as we have tried to show, sufficient for describing many of the observed facts.

What can we say now about the nature of the fireball? It is beyond the scope of this note to give a review of theoretical papers connected with our problem, so we are discussing question only from phenomenological point of view.

One approach is to consider fireballs as kinematical effects and multiple production as an uncorrelated process.

It is also feasible, on the other hand, to regard the produced mesons forming a separated group as dynamically boud. If this should be the case, there would be correlations between the particles forming a fireball. Such correlations do not follow from phase space calculations, but we think that they are compatible with notion of the fireball.[1] Defining the fireball as before, we required only that in the fireball rest frame the angular distribution of the particles should be isotropic and that the single particle energy distribution should be consistent with the phase space. In fact in the accelerator energy range correlations have been already observed leading for example to the so called Goldhaber effect [14].

Taking this possibility into account we can try now to extend our definition by saying that fireballs might be bodies which in the final state form groups of mesons in which the single particle distributions are isotropic and phase space-like in the rest system of the group.

So far there is no clear evidence of the existence of such bodies. Information about them could be obtained if we could observe them before decay. Perhaps information in this matter may be obtained from studies of fireball production inside heavy nuclei, *e. g.* by studying jets produced by primary nucleons in collisions with Ag or Br-nuclei in emulsions. It has been shown by Hołyński *et al.* [15] that jets produced in central collisions of nucleons at energies around 1 TeV with heavy nuclei in emulsions can be well described by the fireball model applied in subsequent collisions inside the nucleus, assuming that fireballs interact

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[1] I wish to thank Dr K. Zalewski for this remark.

with a very small cross-section. A recent investigation of Rybicki and Wolter [16] of jets produced by nucleonic fragments with well known energies confirmed this observation.

It seems that it would be possible to draw some conclusions about the nature of the fireball if a difference would be found in the interaction with nucleonic matter of a fireball, as a dynamically bound system, in comparison with interaction of free pions generated in an uncorrelated process in the form of a collimated beam.

Similar problems are now investigated in elementary particle physics. We mean here cross-section measurements for interactions of very short-lived resonances with nucleons inside the nucleus (*Cf. e. g.* Ref. [16]).

So we can conclude that the production of fireballs, defined as proposed in the paper, is established in a wide energy interval at high energies. It seems, however, that we need more accurate data both from experiments and theory to understand the dynamics of fireball production.

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