Alignment in gamma-hadron families of cosmic rays and interaction characteristics at $E_0 \sim 10^{16}$ eV

I. P. Ivanenko, V. V. Kopenkin, A. K. Managadze, and I. V. Rakobol'skaya
Scientific-Research Institute of Nuclear Physics, Moscow State University, 119899, Moscow

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An alignment of the basic energy fluxes in families of cosmic-ray particles along a straight line has been observed. This effect depends on the interaction energy. It is evident that the separation of the secondary particles in nuclear-interaction events at heights not far above the apparatus is coplanar at ultrahigh energies ($E_0 \geqslant 10^{16}$ eV).

Introduction. In an analysis of families of cosmic-ray particles detected in x-ray emulsion chambers[2,3] in research by the Pamir collaboration,[1] several events having three or four halos were noted. In most of the families (in 5 of 6), these multiple halos were aligned along a straight line.

We have proposed[4] another, more general approach to the study of alignment: analyzing energetically distinct centers. Such centers reflect the most energetic particle fluxes in a family incident on the chamber. They include the following entities: (a) a halo of electromagnetic or hadronic origin (or an individual halo center); (b) a gamma cluster (i.e., a tight group of γ rays which are associated with each other on the basis of corresponding criteria;[5] (c) an individual high-energy γ ray; and (d) a high-energy hadron (after the correction for k_γ upon detection in the chamber).

This approach makes it possible to analyze gamma-hadron families of arbitrary energy for alignment. As a result, it becomes possible to sharply increase the statistical base of these events (by a factor of 10) and to see the energy dependence of the effect. The incorporation of the hadronic and electromagnetic components in a joint analysis strengthens the physical foundation of the analysis. The alignment in events with multiple halos can be regarded as a particular case of the alignment of energetically distinct centers.

The asymmetry parameter λ is used as a measure of alignment.[6] An event is regarded as aligned if λ approaches 1. It turns out that the most effective procedure is to select events from the 4 highest-energy centers with the criterion $\lambda_4 \geqslant 0.8$, since this approach makes the effect most prominent above the computational background.

Results. For an analysis of the alignment effect, we used 74 gamma-hadron families from deep (60-cm) lead x-ray emulsion chambers with energies in the range $\Sigma E_\gamma = 100$–5000 TeV. For comparison with the computational fluctuation background, we used the results of a Monte Carlo simulation of randomly incident points. We also used some artificial families generated by the Monte Carlo method from the MSF quasiscaling interaction model.[7]

Figure 1 shows an example of an experimental event with alignment. Figure 2

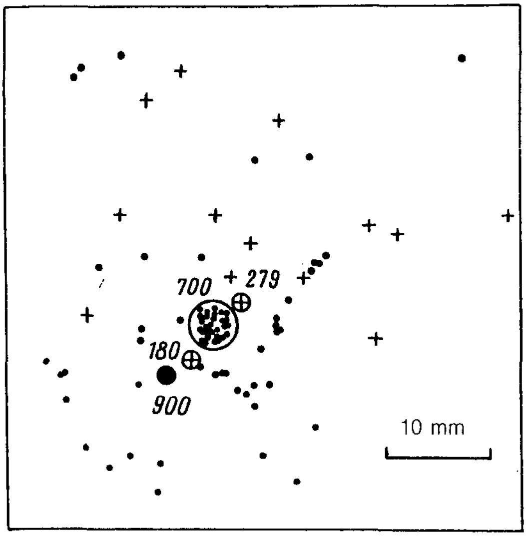

FIG. 1. Representative target diagram with energetically distinct centers for an event with alignment ($\lambda_4 = 0.95$). The numbers are the energies of the energetically distinct centers, in TeV. Energetically distinct centers: O—Electromagnetic halo; ⊗—hadronic halo; ⊕—hadron. Particles of family: ●—γ rays; +—hadrons.

shows the relative number of aligned events versus ΣE_γ. We see that there is essentially no alignment at $\Sigma E_\gamma \approx 100$ TeV, that the effect increases with the energy, and that at $\Sigma E_\gamma \approx 1000$ TeV the effect is quite distinct from the computational background ($43 \pm 17\%$ and 8%).

A statistical analysis using Spearman's rank correlation coefficient[8] has shown that the increase in the relative number of events with alignment with increasing ΣE_γ is indeed real, at a confidence level of 95%. When we apply the Kolmogorov–Smirnov test[9] to the distribution of events with respect to λ, we find confirmation, at the same confidence level, that the experimental data differ from the computational background.

This high relative number of aligned events is observed in deep lead chambers. In lead-carbon x-ray emulsion chambers (C chambers), of a different design,[2,3] the relative number of aligned events detected has been substantially lower, but still distinct from the computational background (Fig. 2). The explanation lies in the particular features of the detection of hadrons in C chambers. A Monte Carlo simulation showed that, because of the distribution with respect to k_γ in the energy prominence of the hadron in the interaction in the chamber, the relative number of events with alignment may decrease from 100% above the chamber to 40% after the detection, even in a deep lead chamber. Because of the methodological distortions of a C chamber, there may be a further decrease from 40% to 13% (Fig. 2).

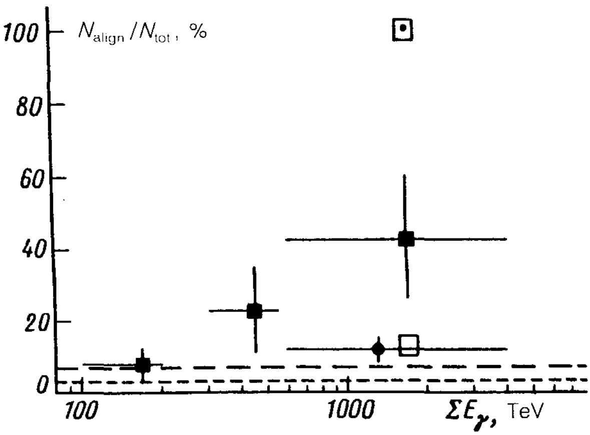

FIG. 2. Relative number of events with alignment versus the energy of the family. The points are experimental data. ■—Deep lead x-ray emulsion chambers; ●—C chambers; ⊡—100% of events with alignment at the boundary of the chamber; □—estimate of the change in the relative number of events with alignment due to the distortions introduced by the C chambers. Long-dash line) relative number of events with an alignment among artificial families (the MSF model); short-dash line) relative number of aligned events with four randomly incident points.

Relationship between alignment and other characteristics of families. Fourteen experimental families with $\Sigma E_\gamma \geqslant 500$ TeV were divided into groups which did and did not exhibit alignment. For these two groups, we analyzed such characteristics as the multiplicity, the γ-ray and hadron spectra within each family, the energy of the hadrons as a fraction of the total energy of the family, the average radii, and the average ER's of both groups of families. No substantial differences between the characteristics of the two groups were found, within the statistical errors.

Momenta of energetically distinct centers. Let us analyze the transverse momenta of the energetically distinct centers both within a jet of four such centers and of the overall jet with respect to the axis of the family. In an x-ray emulsion chamber, it is not the particle's p_t itself which is measured but its approximate analog ER. Under the assumption that the particles are formed in a single interaction at some height H above the chamber, we would have $p_t H = ER$, where R is the distance from the interaction axis.

For families with $\Sigma E_\gamma \geqslant 500$ TeV, the value of $\langle \mathrm{ER} \rangle$ within a group of four energetically distinct centers for events with alignment is 2.1 ± 0.8 GeV·km, while that for events without alignment is 1.8 ± 0.5 GeV·km. The values of $\langle \mathrm{ER} \rangle$ for the entire jet of four energetically distinct centers with respect to the shower axis are 9.2 ± 3.2 GeV·km for events with alignment and 10.1 ± 3.5 GeV·km for events without alignment. The events of the two groups thus do not differ in the value of $\langle \mathrm{ER} \rangle$.

The average ratios of the longitudinal and transverse components of p_t (longitudinal and transverse with respect to the alignment direction in the observation plane) are 11 (for events with alignment) or 4 (for events without alignment). A sharp difference is natural here; it is a consequence of the very separation of the events into two groups. We see that the aligned particles leave the plane of coplanarity with $\langle p_t^{\perp} \rangle \approx 0.1 \langle p_t \rangle$.

If we adopt $H = 2$ km as the most probable interaction height, on the basis of an analysis of the halos of superfamilies,[10] we estimate $\langle p_t \rangle$ within a jet of four energetically distinct centers to be ~ 1 GeV/c.

A further analysis shows that the values of $\langle \mathrm{ER} \rangle$ for the energetically distinct centers of the two groups of events agree well with calculations from the MSF model[7] for small families ($\Sigma E_\gamma = 100$–500 TeV). The values increase with the energy and become substantially higher than the calculated values at $\Sigma E_\gamma \geqslant 500$ TeV.

Energy distribution among the four most energetic structures of the family. Figure 3 shows distributions with respect to the relative energy $E_i / \Sigma_{i=1}^4 E_i$ for model families (MSF) over the energy ranges $\Sigma E_\gamma = 100$–500 TeV and $\Sigma E_\gamma \geqslant 500$ TeV and also for experimental gamma-hadron families in the same ranges. The shape of the distribution does not change with the energy ΣE_γ in the artificial families. In the experimental families, on the other hand, the shape is the same as the calculated shape at low energies, while for the superfamilies the shape is significantly different from the curve for the artificial families and also significantly different from the points corresponding to experimental results at lower energies.

In this representation, a function which drops relatively sharply corresponds to a relatively hard energy spectrum for the production of particles in the interaction event. The solid line shows the distribution with respect to the relative energy for the four most energetic particles produced directly in the interaction in the MSF model at $E_0 = 10$ PeV. The points for a superfamily are close to the calculated distribution, undistorted by a cascade, in a nuclear interaction in the quasiscaling model.

Consequently, in singling out energetically distinct centers experimentally we are in practice observing the fragmentation part of the particle production spectrum in the event, slightly distorted by the cascade and by the detection apparatus. It follows that the most energetic objects of most superfamilies are produced in a single interaction at

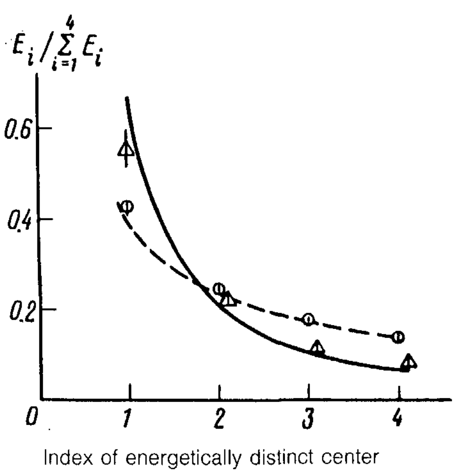

FIG. 3. Distribution with respect to the fraction of the energy among the four energetically distinct centers in a family. The points are experimental (deep lead x-ray emulsion chambers): O—$\Sigma E_\gamma = 100$–500 TeV; Δ—$\Sigma E_\gamma \geqslant 500$ TeV. The lines show results according to the MSF Model: solid line—Directly in the interaction at $E_0 = 10$ PeV; dashed line—artificial events for an arbitrary ΣE_γ.

a relatively small height above the apparatus. (At a greater height, the particles are strongly affected by the cascade.)

Discussion and conclusion. The alignment of the fluxes of energy (or particles) in families at the observation level is a consequence of an asymmetry in the separation of particles in the nuclear interaction. Such an asymmetry does not conform to the interaction model. As was shown in Ref. 11, the earth's magnetic field could not be responsible for any significant asymmetry.

Feĭnberg[12] has attempted to explain the existence of aligned halos on the basis of a model of the production and breakup of a gluon rope in the scattering of a quark by an antiquark. Halzen and Morris[13] have offered an explanation for the existence of aligned halos within the framework of quantum chromodynamics on the basis of a model of semihard jets (with $p_t > 3$ GeV/c). Both those interpretations fail, however, because of energy considerations.

It follows from general considerations (supported by calculations[11]) regarding the development of nucleon-electron cascades (NEC) that alignment in a family should be due to a single interaction. This interaction would be characterized by a high degree of coplanarity of the secondary particles, since in the case of several interactions the development of a NEC would "smear out" the alignment effect. It must be assumed that the primary particle has an interaction range several times as long as that of a proton[11] (i.e., that the particle interacts deep in the atmosphere, not far from the apparatus).

Our estimates based on the MSF quasiscaling model[14,15] show that the probability that families with $\Sigma E_\gamma \geqslant 500$ TeV are produced by primary cosmic rays with an energy $E_0 > 2$ PeV is 1–2%. Estimates from models with an increasing total elasticity coefficient[16] lead to an even lower probability for the production of a γ-ray family and to a significant increase in E_0^{thr}. Consequently, although many important properties of "exotic" interactions with alignment are not yet known, we can assert, even before detailed calcuations have been carried out, that the existence of these interactions would cause essentially no change in the characteristics of extensive air showers or other high-energy cosmic-ray components. Note that the value of E_0^{thr} is close to the energy of the change in slope of the spectrum of primary cosmic rays. Note also that attempts[17] have been made to explain this slope change in terms of a sharp change in the characteristics of hA interactions.

Since the relative number of aligned events may be distorted by the particular features of the procedure used to detect the hadrons by the chamber, we regard it as highly likely that 100% of the events incident on the chamber at $\Sigma E_\gamma \geqslant 1000$ TeV ($E_0 \geqslant 10^{16}$ eV) have aligned, energetically distinct centers, but we are observing the alignment in only some of these events. This interpretation would also account for the fact that essentially all of the other average characteristics of families, with and without alignment, are the same. In other words, in this energy range we are seeing interactions of only a single type (with alignment), not of two types.

In summary, the experimental events in the region of superfamilies can be interpreted as originating at a small height above the chamber and always in interactions with a coplanar separation, at least for the four particles with the highest energies. The spectrum of secondary particles in the fragmentation region is fairly hard and is approximately the scaling spectrum. This conclusion agrees with studies based on an analysis of superfamily halos,[10] in which the average effective height above the chamber at which the halos are produced has been estimated to be ≈ 4 c.u. (i.e., 2 km). If we adopt this height, we find that the average transverse momentum of the secondary particles in a jet of four energetically distinct centers is $\langle p_t \rangle \approx 1$ GeV/c, and the deviation from coplanarity may be $\langle p_t^{\perp} \rangle \approx 0.1$ GeV/c.

[1]Pamir Collaboration, Izv. Akad. Nauk SSSR, Ser. Fiz. **49**, 1285 (1985).

[2]Pamir Collaboration, Trudy FIAN SSSR **154** (1984).

[3]Chacaltaya and Pamir Collaboration, Nucl. Phys. B **370**, 365 (1992).

[4]Pamir Collaboration, Izv. Akad. Nauk SSSR, Ser. Fiz. **55**, 650 (1991).

[5]L. T. Baradzeĭ *et al.*, Preprint N103, P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow, 1974.

[6]Pamir Collaboration, Izv. Akad. Nauk SSSR, Ser. Fiz. **50**, 2125 (1986).

[7]I. P. Ivanenko *et al.*, Preprint N90-21/167, Part I, Scientific-Research Institute of Nuclear Physics, Moscow State University, 1990.

[8]G. J. Glasser and R. F. Winter, Biometrika **48**, 444 (1961).

[9]F. J. Massey, J. Am. Stat. Assoc. **46**, 68 (1951).

[10]Pamir Collaboration, *Proc. 22 ICRC*, Vol. 4, 1991, p. 125.

[11]R. A. Muhamedshin and S. A. Slavatinsky, *Proc. 22 ICRC*, Vol. 4, 1991, p. 225.

[12]E. L. Feĭnberg, in: *Problems of Cosmic-Ray Physics*, Nauka, Moscow, 1987, p. 138.

[13]F. Halzen and D. Morris, *Proc. 21 ICRC*, Vol. 8, 1990. p. 18.

[14]Chacaltaya and Pamir Collaboration, *Proc. 22 ICRC*, Vol. 4, 1991, p. 93.

[15]I. P. Ivanenko *et al.*, Preprint N91-18/222, Part II, Scientific-Research Institute of Nuclear Physics, Moscow State University, 1991.

[16]R. A. Muhamedshin and A. Krys, Preprint N13.42/90, Lodz Univ., Poland, 1990.

[17]S. I. Nikolsky *et al.*, *Proc. 22 ICRC*, Vol. 4, 1991, p. 269.

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