Alignment in γ-hadron families of cosmic rays

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The alignment of the main fluxes of energy in a target plane is found in families of cosmic ray particles detected in deep lead x-ray chambers. The fraction of events with alignment is unexpectedly large for families with high energy and a large number of hadrons. This can be considered as evidence for the existence of coplanar scattering of secondary particles in the interaction of particles with superhigh energy, $E_0 \gtrsim 10^{16}$ eV. Data analysis suggests that the production of most aligned groups occurs slightly above the chamber and is characterized by a coplanar scattering and quasi-scaling spectrum of secondaries in the fragmentation region. The most elaborated hypothesis for the explanation of the alignment is related to the quark-gluon string rupture. However, the problem of the theoretical interpretation of our results still remains open.

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I. INTRODUCTION

The international Pamir Collaboration is conducting a cosmic ray experiment at an altitude of 4400 m above sea level in the Pamir mountains. Primary cosmic ray particles incident upon the atmosphere produce nuclear-electromagnetic cascades of secondaries in air. Hadrons and electromagnetic particles related genealogically are called "family" particles. γ-hadron family features depend on the interaction of hadrons with nuclei in air.

Experimental data accumulated during more than the past 20 past years may allow us to study interactions at very high eneries (up to $E_0 \sim 10^{16}$ eV). These energies are beyond the present accelerator range, and new phenomena may reveal themselves in this region.

A. Installation

The Pamir experiment equipment consists of x-ray emulsion chambers of two kinds: carbon chambers (C chambers) and deep lead chambers (Pb chambers).

Pb chambers (see Fig. 1) are assembled of many sheets of lead of thickness 1 cm, interlaid with x-ray films. The total depth of each Pb chamber is from 40 cm ($\approx$70 c.u.) up to 110 cm ($\approx$195 c.u.). A thick lead substance provides both the few interaction lengths for hadrons and the quasicalorimeter regime for the energy determination of particles.

The C chamber [1] consists of a block of 60 cm of carbon covered on both sides by blocks of lead of thickness 6 cm at the top and 5 cm at the bottom. Each block of lead contains three layers of x-ray film. The carbon block provides the large cross section of the hadron interaction, while the lead blocks are of minimal thickness allowing the determination of particle energies.

The total area of the chambers is a few tens of square meters. Once a year all these chambers are disassembled, the films are taken away, and the results of the experiment are investigated. The results to be reported in this paper have been obtained using deep Pb chambers, which have some advantages in hadron detection efficiency and energy determination accuracy. On the other hand, C chambers possess a larger area of exposure. A comparison with some data from carbon chambers will be given here too.

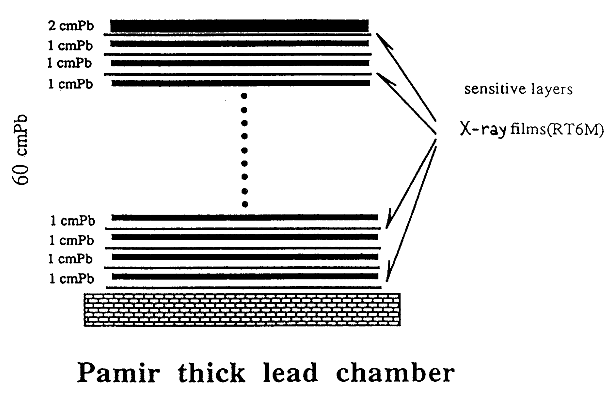

FIG. 1. Structure of the most-used deep lead chamber of 60 cm thickness from Pamir experiment.

B. Experimental procedure

Cosmic ray γ quanta and hadrons create electron-photon cascades (or showers) in the lead. [The term "γ quantum" is conventionally used for both γ quanta and electrons (positrons).] These showers are detected in the x-ray emulsion film as dark spots of a size which is typically smaller than 1 mm.

The darkness density $D(E,t)$ of each spot depends on the energy E of the cascade and on the depth t of its development in a chamber. Comparing $D(E,t)$ for every shower with theoretical predictions one can obtain the energy of each cascade and, consequently, the energy E_γ of a γ quantum incident upon a chamber and producing this shower in it. By doing so for hadrons, one can determine the energy $E_h^{(\gamma)}$ released into the electromagnetic

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component within the installation. It differs from the hadron energy E_h^0 at the chamber surface by the factor k_γ which is around 1/3 for pions.

γ quanta produce electron-photon cascades in the upper part of a chamber only, whereas hadrons produce such showers at large depth as well. The criterion for hadron identification in families is that the breakthrough of a particle in a chamber (i.e., the shift of the origin of the cascade curve) has to be greater than 6 c.u. In this case only a few percent of admixture of the misidentified γ quanta is present among particles classified as hadrons.

The efficiency of the hadron detection is about 70–80 % on average for Pb chambers, and about 55% for C chambers. All chambers have an energy determination threshold around 4 TeV for E_γ and $E_h^{(\gamma)}$ (or around 12 TeV for E_h^0 correspondingly).

While dealing with γ-hadron families one can reconstruct the target diagram of an event by measurement of the coordinates and incidence directions of particles in the film emulsion. Thus one can find such characteristics of a family as the total energy of γ quanta $\sum E_\gamma$ or the total energy of hadrons released to γ quanta $\sum E_h^{(\gamma)}$, the distributions of γ quanta and hadrons in the event area, E_γ or $E_h^{(\gamma)}$ spectra, etc. All families in our experiment were classified by the value of the total energy of the γ component $\sum E_\gamma$. Families with $\sum E_\gamma \geq 100$ TeV are under consideration here. When studying "superfamilies" with $\sum E_\gamma \geq 1000$ TeV it was found that in the central region of the event one can often see one or a few large diffuse dark spots (halos) in the x-ray films, of a size from several millimeters up to a few centimeters. Each such halo appeared usually as a result of the development of an atmospheric electron-photon cascade from a high energy γ quantum produced at some altitude above the chamber [2, 3].

In the lower part of a deep lead chamber one can also find large spots looking like small halos, but having hadronic origin [4]. Each such halo is the result of a cascade produced by a hadron of very high energy in lead (with $E_h^{(\gamma)}$ about 200–500 TeV).

C. History and formulation of the problem

In 1985 the Pamir Collaboration found several families with three or four halos of electromagnetic origin [5, 6], and in most of these families (in five out of six such families) the multiple halos were aligned more or less along a straight line. Experimental results obtained during the subsequent years did not increase considerably the statistics for investigation of such events, but the relative fraction of events with aligned multiple halos of electromagnetic origin became smaller.

As an alignment criterion the parameter of asymmetry introduced by Borisov [7] is conventionally used:

$$\lambda_m = \frac{\sum\limits_{i\neq j\neq k=1}^{m} \cos 2\varphi_{ijk}}{m(m-1)(m-2)} \ . \tag{1}$$

Here m is the number of objects, i, j, k stand for vertices, and φ_{ijk} is the angle between two vectors $\overline{ki}$ and $\overline{kj}$. An event is considered as aligned if $\lambda \geq 0.6$. (A stronger requirement is $\lambda \geq 0.8$.)

The parameter λ_m is the best known parameter of asymmetry describing the degree of alignment rather than the eccentricity. For example, λ_4 will be equal to 1 if four points belong to the same straight line, but it will be far less than 1 if these points form four vertices of a long rectangle.

To have a grasp of the fluctuation background, i.e., the probability of random occurrence of alignment during the development of the nuclear-electromagnetic cascade, a computer simulation of families with multiple halos was made [8, 9] using a quasiscaling model without any specific mechanisms for producing asymmetry [10]. The relative fraction of events with three aligned halos in the simulated families appeared to be rather high, about 30–35 % (by the criterion $\lambda_3 \geq 0.6$).

The level of background noise calculated for three random incident points (or "particles" not belonging to the same cascade) was given as 24% by the same criterion. Therefore an appropriate analysis of the phenomenon to isolate the effect from the fluctuation background became essential.

However, in the papers [5, 6] discussed above only halos at the same (small) depth in the upper part of the C chambers were considered under some constraint on the level of darkness D of the spots in x-ray films. Experimental results obtained in Pb chambers allowed one to investigate the alignment of multiple halos at different observation depths and at various levels of darkness D, and to take into account the contribution of hadron cascades (hadronic halos) in the lower part of a chamber [8]. It was found that the alignment of multiple halos in the same family is a function of both the depth and the level of darkness D used for halo identification. Therefore this approach seems physically inadequate.

It is worth mentioning here that an attempt to investigate the asymmetry of family particle configuration (separately for the γ component and for hadrons) in events of small energies ($\sum E_\gamma = 100$–400 TeV) was made in [11]. It was found that there was some excess of asymmetry in experimental events over simulated ones. However, the analysis was carried out with a quite different criterion of asymmetry α, and the existence of such asymmetry did not necessarily imply alignment.

In the investigation of alignment we tried to find a better method of selection of objects to be examined, which would be more sensitive and less dependent on methodological factors. In [9, 12] it was suggested to consider not only halos, but a more general class of objects, which were called "energy distinguished cores" (EDC's). These objects in the x-ray film correspond to the centers of the most prominent jets (air cascade branches) with the highest energies in a family. They include the following objects: (a) halos of electromagnetic origin (or separate cores of a multiple halo); (b) γ clusters (i.e., compact groups of γ quanta which are combined into clusters using the criterion of decascading); (c) γ quanta isolated from clusters and halos; (d) hadrons (in particular, the

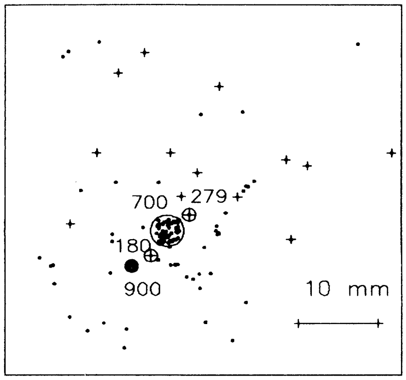

FIG. 2. An example of the target diagram with energy distinguished cores for the event with alignment (the family Pb-6). λ_4=0.95. Figures in the plot stand for energy in TeV (already multiplied by 3 for hadrons). EDC: ⊛ is the halo of electromagnetic origin; ● is the hadronic halo; ⊕ are the high energy hadrons; • are the family γ quanta; + are the hadrons of the family.

hadrons which produced halos in the chamber).

In order to treat the γ component and hadrons in a similar way, one should multiply by the factor of 3 the energy $E_h^{(\gamma)}$ released by a hadron in the chamber into the electromagnetic component, since most secondaries in a family are pions and the average fraction of energy transferred by pions to the electromagnetic component is approximately equal to 1/3.

All family particles may be classified in such four types (a)–(d) of objects (cores). Then all cores are considered in the order of decreasing energy, so it becomes clear how to select the three or more most energetic objects in each family for analysis. The maximal possible number of cores considered in each family is limited only by the multiplicity of particles in the event. For superfamilies (i.e., events with $\sum E_\gamma \geq 1000$ TeV) this number may run to a few hundreds of observed particles; that is why we called such selected objects EDC's (energy distinguished cores). Low energy families (with $\sum E_\gamma$ about 100 TeV) contain sometimes not more than three such cores (usually these are simply separate γ quanta and hadrons). It is worth noting here that at high energy, where the alignment effect becomes essential, selected EDC's have energies at least a few times higher than the detection threshold 4 TeV.

This approach allows one to study alignment in γ-hadron families of not very high energies when there are no halos, and to avoid discrimination of some types of EDC's against some other ones. By this method the investigation became effective and physically equivalent for both charged secondaries in an atmospheric shower (family hadrons) and neutral secondaries (γ component in the same family), combining them to describe the interaction above a chamber.

To investigate the alignment of all family cores, which are detected at different depths in the chamber, a target diagram was made by projecting all traces of EDC's onto one plane (for example, onto the plane of the chamber top surface). If the zenith angle of an event was not zero, the family image was transformed to the normal plane. Alignment of the energy distinguished cores was studied in this plane; see, e.g., Fig. 2.

II. RESULTS

A. Experimental statistics

In this work we have analyzed 68 γ-hadron families from deep lead chambers with the total energy of the γ component $\sum E_\gamma \geq 100$ TeV, the number of γ quanta $N_\gamma \geq 3$, and the number of hadrons $N_h \geq 1$ (see Table I). In our data bank there are also 19 families with $N_h = 0$ which were not used in this work, since we were looking only for γ-hadron families. Among these 68 events there are 18 families with $\sum E_\gamma \geq 500$ TeV; see Table II. (Such high energy events were collected from a larger area of the installation than lower energy ones.) The total exposure of Pb chambers here in use is about 450 m^2 yr. As for the hadron component, 13 events with $N_h > 10$ are present in our data.

For comparison in some figures we also show the data from carbon chambers of the Pamir Russia-Japan Joint Experiment. This set contains 84 γ-hadron families with $\sum E_\gamma$ = 100–2600 TeV (see Table I) from total exposure around 440 m^2 yr. These results were obtained using Japanese x-ray films from Pamir chambers measured in Waseda University (Tokyo) and analyzed with the participation of the authors.

B. Evidence of alignment

To find the effective criteria of alignment for analysis, we tested various threshold values of λ and variants including different numbers of cores (EDC's) in a family. The best ratio of the signal to the fluctuation background with satisfactory statistics appears with the alignment criterion $\lambda_4 \geq 0.8$. However, versions with other numbers of EDC's are also shown in our figures. The pro-

TABLE I. Experimental events in use: the number of γ-hadron families with $\sum E_\gamma \geq 100$ TeV, $N_\gamma \geq 3$, and $N_h \geq 1$.

$\sum E_\gamma$ (TeV)	100–300	300–500	>500	Total
Pb chambers	35	15	18	68
C chambers (Rus.-Jap.)	57	12	15	84

TABLE II. Families from deep lead x-ray chambers with $\sum E_\gamma \geq 500$ TeV or $N_h > 10$.

Name of event	N_γ	$\sum E_\gamma$ (TeV) $E_\gamma \geq 4$ TeV	N_h	$\sum E_h^{(\gamma)}$ (TeV) $E_h^{(\gamma)} \geq 4$ TeV	Halo	Alignment by criterion $\lambda_4 \geq 0.8$
LoLiTa	386	6140	31	699	+	+
Pb-45	312	4574	44	1055	+	+
Pb-28	195	3069	59	824	+	+
Pb-3703	180	2559	23	690	+	—
Pb-53	120	2071	44	727	+	—
Pb-8	192	1964	33	621	+	—
Pb-6	91	1521	44	816	+	+
Pb-54	111	1291	30	336	—	—
F73-9	76	949	11	297	—	+
Pb-20	61	897	22	637	+	+
Pb-3704	47	890	7	352	+	—
Pb-6012	48	668	4	53	+	+
Pb-2	60	752	3	130	+	—
Pb-2105	63	687	5	56	—	+
Pb-6013	58	794	12	188	+	—
Pb-58	75	625	23	1086	+	—
Pb-4711	29	575	3	144	—	—
Pb-5901	47	501	2	71	+	—
Pb-2201	35	390	12	125	—	+

posed approach allows us to follow the behavior of the fraction of events with alignment as a function of $\sum E_\gamma$, representing the family energy.

In Figs. 3(a), 3(b), and 3(c) one can see such dependence for respectively three, four, and five energy distinguished cores selected in each family in order of decreasing energy. It would be inefficient to include too many EDC's from each family in consideration since the observation of alignment for many objects demands very numerous experimental statistics in order to be seen. (An obvious reason is the low probability of alignment for many objects. For example, only one event with seven aligned EDC's is present in the available experimental material.)

The two dashed lines in each figure show the levels of accidental occurrence of alignment in model simulations (i.e., in artificial γ-hadron families) and in simulated groups of randomly incident objects. One can see that the fluctuation background level is always higher in model events due to correlations in a cascade. The model which we have used [10] does not involve any special mechanism of asymmetry. Simulation results on accidental alignment due to fluctuations are in practice not sensitive to the nucleus atomic number. In additon, the overwhelming majority of detected superfamilies at the Pamir altitude should be from proton primaries [13]. Hereafter the criterion $\lambda \geq 0.8$ is used for classification of the families with alignment.

An increase of the fraction of events with alignment is evident for families studied in deep lead chambers. This fraction rises from the background level at $\sum E_\gamma = 100$–300 TeV to $(61 \pm 18)\%$ for three cores under consideration and to $(47 \pm 17)\%$ for four EDC's at $\sum E_\gamma \geq 500$ TeV.

It is worth noting that an additional analysis has been performed where we have studied the behavior of the alignment fraction with energy when various kinds of energy distinguished cores were considered separately. According to this analysis, the fraction of events with alignment appears to be independent of energy for the γ quanta under consideration, but increases with energy for both γ clusters and hadrons. The fraction of events with alignment for γ quanta stays at the level of the fluctuation background, since the electromagnetic cascade mechanism violates the original configuration of γ quanta even if they were aligned at the interaction point. The characteristic length of development of a nuclear cascade in the atmosphere is a few times greater than for the electromagnetic one. Therefore hadrons and γ clusters identified with charged secondaries in the interaction better preserve their original configuration. However, the increase of alignment with energy for γ clusters or hadrons is less prominent than the similar rise for EDC's, where these two kinds of objects are included into consideration together with halos and γ quanta.

Such behavior of different kinds of energy distinguished cores confirms indirectly our understanding of the role of every component of a family in the alignment phenomenon.

The data obtained in the carbon chambers, Fig. 3, show the same tendency as the data obtained in the lead ones, but the increase of the alignment effect for the C chamber data is somewhat less prominent. There may be several reasons for this difference. The data from C chambers for maximal energy range are poor in the high energy events as compared with Pb chambers. In addition, the hadron detection efficiency for the C chambers is considerably lower than for the Pb chambers, and missed hadrons may destroy the display of alignment under consideration.

In Fig. 3(b) one can see the estimated value of the fraction of events with alignment if the thickness of the lead chambers were equivalent to the thickness of the carbon ones. This value seems to be in agreement with the C chamber data. The accuracy of energy determination for hadrons in carbon chambers (especially for high energy particles) is also lower than in the Pb chambers, where the multilayer method allows one to follow a complete cascade curve from a particle, in contrast to only one or two points over a lead block in carbon chambers.

The existence of the alignment effect is supported by the fact that the experimental point at $\sum E_\gamma \geq 500$ TeV [see Fig. 3(b)] stays at two standard deviations above the fluctuation background level. If we estimate the combined significance of the deviation from the background

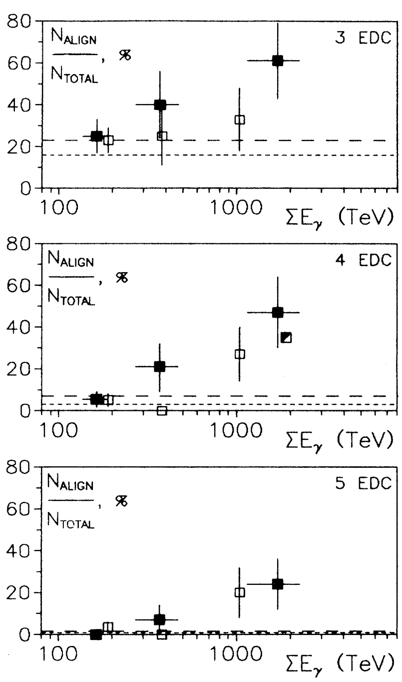

FIG. 3. Dependence of the fraction of families with alignment on total γ component energy of an event $\sum E_\gamma$. $N_{\rm total}$ is the total number of families in a given energy range; $N_{\rm align}$ is the number of families with alignment in the same energy range; (a) considering three energy distinguished cores (EDC's) in each family; (b) considering four EDC's in each family; (c) considering five EDC's. Experiment: ■ is for Pb chamber data; □ is for C chambers of the Pamir Joint Experiment (data bank of Waseda University); ◩ is for the estimate of probable result of Pb chambers having a reduced thickness equivalent to the C chambers one. Simulations: ---- is for the artificial families by the quasiscaling model without any special asymmetry; - - - is for randomly incident objects.

for two independent points at $\sum E_\gamma = 300$–500 TeV and $\sum E_\gamma \geq 500$ TeV, the χ^2 criterion yields the confidence level[1] $\simeq 99\%$.

Our model simulations of γ-hadron families [14] showed that the best correlation with the primary energy E_0 of the air cascade is obtained not for $\sum E_\gamma$ (or for $\sum E_{\rm total} = \sum E_\gamma + \sum E_h^{(\gamma)}$) but for the number of hadrons in a family, N_h. Fluctuations of N_h at fixed E_0 appeared to be two or three times less than fluctuations of the total γ component energy $\sum E_\gamma$ or the total hadron energy $\sum E_h^{(\gamma)}$ for the same E_0. Therefore, if the effect under consideration has an energy threshold while E_0 increases, the same behavior should be observed as a function of the hadron number N_h, the increase of alignment being even more distinct than while considering the dependence on $\sum E_\gamma$.

In Fig. 4 the dependence of the fraction of events with alignment on the hadron number N_h in a family is presented for various numbers of the energy distinguished cores under consideration. One can see an evident rise of the fraction with an increase of N_h. Thus the results presented in Fig. 4 confirm the sensitivity of the alignment to the number of hadrons in a family. In Pb chambers the fraction of families with alignment comes to $(83 \pm 37)\%$ for three EDC's and $(67 \pm 33)\%$ for four EDC's. The increase of the effect for events from carbon chambers is in agreement with the Pb chamber data. C chamber families are poor in events with large numbers of hadrons. Our comments on the carbon chamber data shown in Fig. 3 are valid for this comparison too.

Figure 5 shows the dependence of the fraction of families with alignment on the number of energy distinguished cores in each family under investigation. One can see that in families with $N_h = 1$–3 it is not higher than the level of the fluctuation background, whereas for the group of events with $N_h > 30$ this fraction is much greater than the calculated background for up to seven cores considered. Despite large statistical errors, this makes an impressive case in favor of the reality and significance of the effect under consideration, of its sufficiently high frequency of occurrence in the range of large N_h, and, consequently, of high energies of the primary particle E_0. The energy scale E_0 where we see a considerable alignment begins at about 10^{16} eV.

Figure 5 also shows the fraction of aligned events in accelerator data at $E_0 = 250$ GeV (target experiment NA22 at CERN, π-Au interaction [15]). These results are in remarkable agreement with the results of our model simulations of the background level. This confirms the methods which we have used in our simulations, as well as our conclusion that alignment is a threshold effect which occurs only at sufficiently large energies.

[1]The standard deviation is assumed to obey Poisson statistics, since the range with prominent alignment is far from the thresholds of the selection criteria.

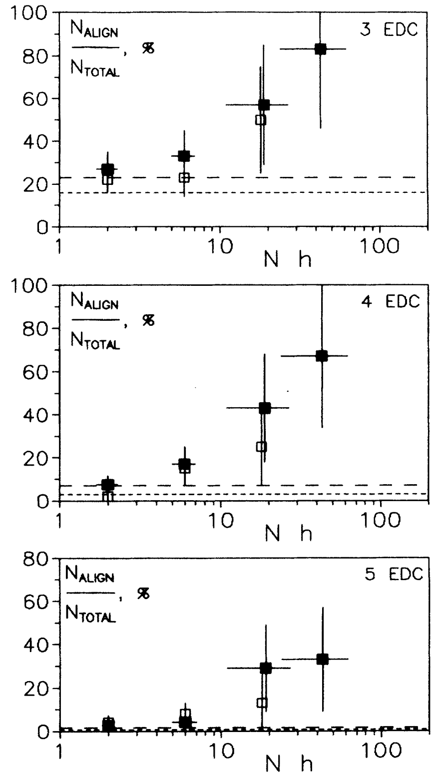

FIG. 4. Dependence of the fraction of families with alignment on the hadron number N_h in a family. (a), (b), and (c) correspond to events with three, four, and five EDC's in each family (see caption to Fig. 3).

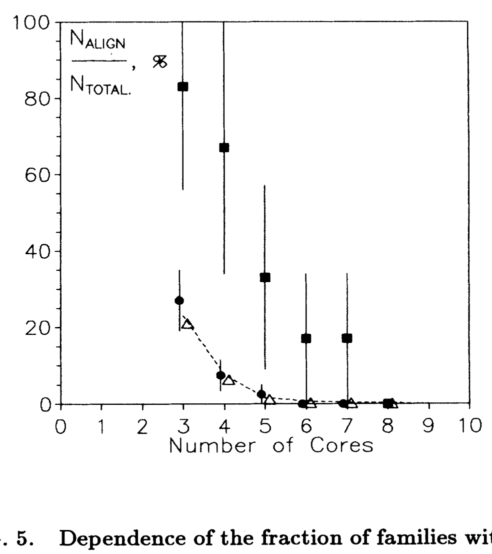

FIG. 5. Dependence of the fraction of families with alignment on the number of energy distinguished cores (EDC's) in each family. For $N_{\rm total}$, and $N_{\rm align}$ see caption to Fig. 3, - - - - is for the model simulation. Experiment: ■ is for the families from deep lead chambers with $N_h > 30$. • is for the families from deep lead chambers with N_h=1–3. △ is for accelerator data at E_0=250 GeV (experiment NA22 at CERN, π-Au interaction).

C. Transverse momenta of energy distinguished cores

The analysis of the transverse momenta p_t of EDC's seems to be of importance in the theoretical explanation of the phenomenon. It is well known that the x-ray emulsion chambers detecting air families are able to measure not p_t itself, but a roughly related quantity ER (where E is the particle energy and R is the distance in the target plane from an axis). The relation between p_t and ER is based on the assumption that the particles are produced in one interaction at some altitude H above an installation. In this case $p_tH = ER$. ER of each core is determined in reference to the energy-weighed center of the ensemble of four EDC's in each family. Such centers correspond to the points of interaction with probable alignment and they may not coincide with the axis of the whole shower, which includes many particles from other interactions inside the same air cascade. Events with $\sum E_\gamma \geq 500$ TeV were analyzed. The average value $\langle ER\rangle$ in this case appeared to be 2.1 ± 0.8 GeV km for events with alignment and 1.8 ± 0.5 GeV km for families without alignment. One cannot see any significant difference in this quantity between the two classes of events.

It seems reasonable also to calculate the average ratio of longitudinal $p_t^{\parallel}$ and transverse $p_t^{\perp}$ (in reference to the alignment direction in the target diagram plane) in the same events for the same four EDC's in each. Such a quantity,

$$\sum p_t^{\parallel} \Big/ \sum p_t^{\perp} = \sum ER^{\parallel} \Big/ \sum ER^{\perp}, \tag{2}$$

is similar to the famous parameter "thrust." The average value $\langle \sum p_t^{\parallel} / \sum p_t^{\perp} \rangle$ was obtained to be ~ 11 for events with alignment and ~ 4 for ones without alignment. This ratio differs considerably for the two cases. This is a natural consequence of separation by the criterion $\lambda \geq 0.8$. Such an evaluation for events with alignment enables us to see that aligned cores come out of the coplanarity plane by $\langle p_t^{\perp}\rangle \sim 0.1\langle p_t\rangle$.

Thus assuming the most probable interaction altitude $H = 2$ km (which follows from the halo superfamilies analysis [4]), $\langle p_t\rangle$ within the group of four EDC's is estimated as ~ 1 GeV/c and $\langle p_t^{\perp}\rangle \approx 0.1$ GeV/c.

D. Energy distribution over the most energetic cores in a family

The energy distribution over four energy distinguished cores in each family is another interesting characteristic. Figure 6 shows the distributions in energy fraction $E_i^{\rm EDC}/\sum_{i=1}^{4} E_i^{\rm EDC}$ for simulated families (quasiscaling MSF model [10]) in the energy ranges $\sum E_\gamma$ = 100–500 TeV and $\sum E_\gamma > 500$ TeV and for experimental families in the same ranges. The shape of the distribution does not change with energy $\sum E_\gamma$ in simulated families, and the shape of the distribution for low energy experimental families agrees with the simulations, whereas the plotted

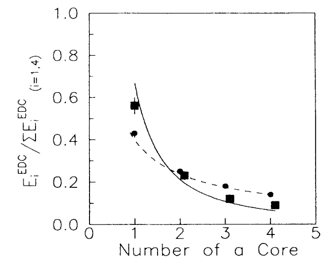

FIG. 6. The distribution of energy fractions over the four most energetic cores in a family. Experiment with deep lead chambers: ■ is for families with $\sum_\gamma > 500$ TeV; • is for those with $\sum E_\gamma = 100$–500 TeV. Simulations by the quasiscaling MSF model [10]: - - - - is for artificial families with any $\sum E_\gamma$; ——— is for secondaries created in a single interaction at $E_0 = 10^{15}$ eV.

points for superfamilies ($\sum E_\gamma > 500$ TeV) differ considerably from both the above mentioned distributions.

In this representation the more steeply the function falls with energy, the "younger" the cascade age is, and the harder is the energy spectrum of the objects under consideration, since repetitive interactions due to the cascade development lead to energy degradation, resulting in softening of the spectrum and equalization of the energy distribution. The solid line shows the distribution in energy fractions over the four most energetic particles produced in a direct interaction in the quasiscaling model at $E_0 = 10^{15}$ eV. It is evident that the distribution for events with $\sum E_\gamma > 500$ TeV is close to the calculated one for particles just after an interaction in the quasiscaling model.

This shows that by investigation of the energy distinguished cores in the experiment we in fact study the fragmentation part of the particle production spectrum; this part of the spectrum being only slightly distorted by the air cascade and by the detecting device. In addition, this implies that the most energetic cores in the majority of the superfamilies under consideration are produced in one interaction at relatively low altitude above the chamber. (Particles coming from a large altitude may undergo a strong cascade effect.)

III. DISCUSSION

Alignment of energy distinguished cores (or particle streams, or energy fluxes) in air families should be related to coplanar scattering in nuclear interactions. It is very hard to explain the results of our experiment in the framework of conventional interaction models. It can be inferred from [16] that the magnetic field of the Earth could not be responsible for any appreciable asymmetry. In the same work the obvious fact that the coplanar "fan" of particle streams may be blurred by the cascade process after a few interaction paths was confirmed by a model simulation. Therefore, either the interaction which leads to the coplanar scattering occurs not far from the chamber,[2] or it may occur more than a few hadron interaction lengths above the chamber. However, in the last case the multiplicity of aligned particles in this "fan" should be large enough to provide the alignment of four cores at the observation level while the other originally aligned particles drop out of the original "fan" plane due to the cascade development.

There are two main problems which should be solved in order to find a theoretical explanation of alignment. First of all, one should identify an interaction mechanism, and then one should solve the problem of the intensity of coplanar events. In the absence of a simple theoretical interpretation of alignment, any guess at the possible interaction mechanism should be carefully considered.

Halzen and Morris proposed an explanation of alignment based on the semihard jet model ($p_t > 3$ GeV) [17]. Such an interpretation does not seem quite satisfactory since EDC's of families are formed by the most energetic fragmentation-region particles, but not by the soft jet particles.

Roizen has suggested interpreting the phenomenon as a projection of quark-gluon string rupture produced in the process of semihard double inelastic diffraction dissociation, the string connecting the semihard scattered fast quark and the incident hadron remnants [18]. Such an explanation seems plausible because the energy threshold of the alignment effect is consistent with the thresholdlike dependence of semihard double inelastic diffraction. According to theoretical predictions [19], being independent of alignment, such a diffraction process should manifest itself progressively at $10^{14} - 10^{16}$ eV. The "length" of aligned groups of EDC's as a projection is also more or less in agreement with the transferred momentum during string production ($Q_t \simeq 3$ GeV/c). In this case the target diagram of a superfamily with alignment may be considered as a direct "photographic" image of such a process.

The average invariant mass M of the entire group of four aligned particles is $\langle M^2\rangle = (60^{+120}_{-60})$ GeV^2. For the group of six aligned particles $\langle M^2\rangle = (150 \pm 150)$ GeV^2. Such an evaluation of M is again more or less compatible

[2]G.T. Zatsepin (private communication) suggested a possibility that high energy interactions (at energies about 10^{16}eV) may be approximately divided into two classes, with small and with large coefficients of inelasticity. In this case there will be some primary particles which do not produce secondaries with observable energy and do not lose significant energy during their first few interactions in the atmosphere. Such particles have a chance to carry high energy through the atmosphere, and if their last interaction occurs not far away from the chamber and belongs to the second class (with large coefficient of inelasticity and therefore with release of main fraction of their energy), then the alignment of the products of this last inteaction of these particles will not be blurred by the cascade process. Under this hypothesis the major part of observed superfamilies should be produced in accordance with this scheme.

with the inelastic diffraction picture [18].

Note that the energy range $E_0 \simeq 10^{15} - 10^{16}$ eV is proclaimed as the threshold for several unusual processes: (a) for the alignment phenomenon; (b) for "Centauro" events production [20]; (c) for the explanation of the electromagnetic particle spectrum in extensive air showers in the experiment "Hadron" [21]; (d) for semihard double inelastic diffraction.

The possible relation of alignment to the string rupture hypothesis has already been mentioned above. It is pertinent to add that the ratio $\frac{\langle p_t^{\perp} \rangle}{\langle p_t^{\parallel} \rangle} \sim 0.1$ within an EDC group is roughly consistent with proper string parameters in transverse momentum space, but as our preliminary model simulations show it may be appropriate to assume very small $\langle p_t^{\perp} \rangle \sim 20$ MeV across the string in order to explain alignment. Such a value has something in common with features of the hypothetical "chiron" event production [22] suggested to appear in the same energy range.

Our group attempted to study the intermittency and fractal structure of superfamilies and to relate these phenomena with alignment. A study of intermittency was earlier carried out in [23–25] in the energy range 0.1–10 TeV for accelerator and balloon data. However, as has been shown above, we did not find any noticeable (exceeding background) alignment at such low energies. Thus at present we do not see any experimental evidence of a direct relation between alignment and intermittency.

Our cosmic ray events under consideration are different from accelerator and balloon target experiment data, since our superfamilies are the result not of a single interaction but of a nuclear cascade in the atmosphere. Such cascades may blur to some extent the display of intermittency in an individual interaction. The possibility of separating cascade effects from the peculiarities of a single nuclear interaction requires further investigation, and we are going to continue our work in this direction.

Nevertheless, some qualitative relation of alignment and intermittency may exist: irregularities at energies 0.1–10 TeV due to the quark-gluon plasma appearance revealed as excessive fluctuations in angular and lateral distribution should become more evident at energies $10^3 - 10^4$ TeV (for example, string production with large transferred momentum that gives an alignment effect in the film plane).

The authors understand that the ideas discussed above do not constitute a complete theoretical interpretation of alignment. However, any hint can be important when discussing events at such a high energy and with such hard-to-reach statistics. An active search for a satisfactory explanation is necessary and is under way.

It would be most desirable to test this effect on accelerators. Preliminary estimates indicate that the energies accessible at Fermilab would be barely enough to produce comparable families. However, one can still obtain interesting results at these energies due to the possibility of having much better statistics than in cosmic rays.

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