Alignment in Gamma-Hadron Families

Detected by Deep Lead X-ray Emulsion Chambers

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ABSTRACT

Alignment of main fluxes of energy in a target plane is found in families of cosmic ray particles detected in deep lead X-ray emulsion chambers. The fraction of aligned events becomes unexpectedly large for superfamilies with the total energy of gamma-quanta exceeding $10^3$ TeV. This can be considered as an evidence of existence of coplanar scattering of secondary particles in interactions of primary particles with superhigh energies ($E_0 \gtrsim 10^{16}$ eV).

Data analysis suggests that production of most superfamilies happens low above the chamber and is characterized by a coplanar scattering and quasising spectrum of secondary particles in the fragmentation region.
1 Introduction

International collaboration “Pamir” is conducting a cosmic ray experiment at the altitude 4400 meters in Pamir mountains. Our equipment consists of X-ray emulsion chambers of two kinds: C-chambers and Pb-chambers. C-chambers consist of a block of carbon covered from both sides by blocks of lead of thickness 6 cm. Each block of lead contains 3 layers of X-ray film. Pb-chambers are assembled from many carpets of lead of thickness 1 cm, interlaid with X-ray film. The total depth of each chamber usually is 60 cm. Once a year all these chambers are disassembled, the X-ray film is taken away and the results of the experiment are investigated. The new results to be reported in this paper were obtained using Pb-chambers.

Gamma quanta and hadrons which are present in the cosmic rays create electron-photon cascades in the lead. These cascades are registered in the X-ray 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 energy \( E \) of the cascade and of the depth \( t \) of its development in the chamber. By comparison of the distribution of \( D(E,t) \) for all spots with the theoretical predictions one can obtain the energy of each cascade and, consequently, the energy of the primary particles producing these cascades. We register particles with energies beginning from 2-6 TeV. Gamma quanta produce electron-photon cascades in the upper part of the chamber only, whereas hadrons produce such cascades at large depth as well. Efficiency of registration of hadrons is about 70%. Such a deep lead chamber works very similar to an ionization calorimeter.

Apart from single particles, this chamber registers also the so-called “gamma-hadron families”. Each such family is a genealogically related group of gamma quanta, electrons and hadrons, which appear as a result of development of a nuclear electromagnetic shower created when the primary high energy cosmic rays enter the atmosphere.

By measuring of the coordinates and directions of motion of particles inside the chamber one can reconstruct the target diagram of the family and find its properties, such as the total energy of gamma quanta in the family \( \sum E_\gamma \), the distribution of gamma quanta and hadrons in the area, the energy released by hadrons to the electron-photon cascades \( E_h^\gamma \), etc. All families in our experiment were classified by the the value of total energy of gamma quanta \( \sum E_\gamma \). We considered families with \( \sum E_\gamma > 100 \) TeV. When we studied “superfamilies” with \( \sum E_\gamma \gtrsim 1000 \) TeV, we have found that near the center of the event at the X-ray film one can often see one or more large diffuse dark spots, of a size from few millimeters to several centimeters. Each such halo usually appears as a result of development of an electron-photon cascade by a high energy gamma quanta at some height above the chamber [1, 2].

In a lower part of a deep lead chamber one can find also large spots which also look like a halos, but have hadronic origin [3]. Each such halo is a result of a cascade produced by hadrons of very high energy (about 100 ÷ 500 TeV) in lead.
In 1985 Pamir Collaboration has found several families with 3 or 4 halos of electromagnetic origin [4, 5], and in most of these families (in 5 out of 6 such families) these halos were aligned. Experimental results obtained during the subsequent years did not increase considerably statistics for investigation of these events, but the relative fraction of events with the aligned halos of electromagnetic origin became smaller.

As an alignment parameter we used the function

$$\lambda_m = \sum_{i \neq j \neq k} \frac{\cos 2\phi_{ijk}}{m(m-1)(m-2)}$$

where $m$ is the number of halos and $\phi_{ijk}$ is the angle between the two vectors, which connect the center of the halo $k$ with the centers of the halos $i$ and $j$ [6]. An event is considered aligned if $\lambda \geq 0.6$. (A stronger requirement is $\lambda \geq 0.8$.)

Parameter $\lambda$ is the best known parameter of asymmetry describing the degree of alignment rather than eccentricity. For example, $\lambda_4$ will be large if four points belong to the same straight line, but it will be small if these points form four vertices of a long rectangle.

We performed a computer simulation of families with several halos using quasiscaling models without inventing any specific mechanisms for producing asymmetry [7, 8, 9]. Relative fraction of events with three aligned halos in the simulated families was rather high, about 30$\div$35%. This number gives the level of background noise, i.e. the level of of fluctuations in the development of the nuclear-electromagnetic cascade. According to simulations, the degree of alignment for three random ‘particles’, which do not belong to the same cascade, was given by 24%.

However, in the works discussed above we registered only halos at the same (small) depth in the upper part of C-chambers, under some constraint on the level of darkness of the spots $D$ on the X-ray film.

Experimental results obtained in Pb-chambers allowed us to investigate alignment of halos at different depths and with different levels of darkness $D$, and to take into account the contribution of hadronic cascades in the lower part of a chamber [4]. We have found that the alignment of halos in the same family is a function of depth and of the level of darkness.

In our 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 a search for such method we proposed to study not only halos, but a more general class of objects, which we called ‘Energy Distinguished Cores’ (EDC) [8, 10]. These objects on the X-ray film correspond to the centers of the most jets with the highest energy in a family. They include the following objects:

- halos of the electromagnetic origin (or separate centers of one halo)
- gamma-clusters (i.e. compact groups of gamma-quanta which are combined into separate clusters using the criterions of (compact decascading) or close,
• separate gamma-quanta of very high energy perhaps)
• high energy hadrons, in particular the hadrons which produced halos in the chamber

In order to treat gamma-quanta 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 in average $<k_{\gamma}> = 0.33$.

This approach allows to analyse alignment in the gamma-hadron families of not very high energies which do not contain halos, and to avoid discrimination of some types of EDC against some other ones. By this method we effectively investigate spatial distribution of the most energetic particles in the shower, where the distribution of hadrons correspond to the distribution of charged particles in the shower, and the distribution of gamma-quanta correspond to neutral secondary particles.

To investigate alignment of all events which occur at different depth in the chamber, we made the target diagram: we projected all events onto one plane by shifting their images along the direction of the shower. After that we studied alignment of all EDC in this plane.

For example, we were looking for alignment of four EDC. In one of the superfamilies there were four electromagnetic halos which were not aligned. However, in the lower part of the chamber we have found two hadrons which had energy higher than the energy of the two halos out of four. After we projected the halos and the hadrons onto the same plane, we have found that the four most energetic events (two halos and two hadrons) were aligned in accordance with the criterion $\lambda_4 > 0.8$.

## 2 Alignment of EDC

To analyse the effect of alignment we studied 74 gamma-hadron families with energies $100 \text{ TeV} < \sum E_\gamma < 5000 \text{ TeV}$, which were found in Pb-chambers. Experimental results were compared with the simulation of random falling down of 3 and 4 points, and with the simulation of a family described by the model of quasiscaling interaction [9].

The most significant deviation of experimental results from the results obtained by the simulations appears if one investigates alignment of four EDC with the alignment criterion $\lambda_4 > 0.8$. At $\sum E_\gamma \sim 100 \div 300 \text{ TeV}$ the fraction of aligned events was $(9 \pm 3 \%)$, at $\sum E_\gamma \sim 300 \div 500 \text{ TeV}$ this fraction was $(23 \pm 10 \%)$. The effect grows with energy, and at $\sum E_\gamma \sim 500 \div 5000$ approaches $(43 \pm 17 \%)$. Meanwhile according to our simulations of families this effect does not depend on energy and is equal to 8\%, whereas the simulation of randomly falling uncorrelated particles gives only 4\%.

Analogous analysis was performed in [11] for other criterions of alignment as well, for example,
for $\lambda_3 > 0.6$ and $\lambda_3 > 0.8$ for three EDC, and for $\lambda_4 > 0.6$ for four EDC. In addition, an investigation of alignment was performed for different components of families: 4 hadrons, 4 gamma-clusters, 4 gamma-quanta. All results are in a good correlation with each other. They show increase of the fraction of aligned events when one goes from gamma-quanta to gamma-clusters, to hadrons, and then finally to EDC.

Statistical analysis with the use of various criteria (rank correlation of Spearman, Kolmogorov-Smirnov criterion) has shown that the experimental results on alignment of EDC at $\sum E_\gamma > 500$ TeV can be distinguished from the background fluctuations in our simulations at 95% confidence level. At the same confidence level, alignment grows with energy $\sum E_\gamma$.

Conditions of registration of particles influence the results because of the limited accuracy of energy determination, and also because of possible deviations of the coefficient $k_\gamma$ from its average value $\langle k_\gamma \rangle = 0.33$. Simulation of different possibilities has shown that an account taken of these effects may increase almost twice the fraction of events in our experimental data which we interpret as aligned. This suggests that the fraction of aligned EDC may be even greater than we thought.

The analysis was made also for every family selecting various number of EDC from 3 to 10. Results for families with small energies come close to the fluctuation level of model simulations. On the other hand, the fraction of aligned events for 14 superfamilies with $\sum E_\gamma > 500$ TeV exceeds by two standard deviations the fluctuation level of model simulations for any particular number of EDC. One should note, however, that statistics is very small. We have found 6 events with 4 aligned cores, 4 events with 5 aligned cores, 2 events with 6 aligned cores and one event with seven aligned cores.

14 superfamilies with $\sum E_\gamma > 500$ TeV were divided into groups with or without alignment. For these two groups various characteristics were analysed. No statistically significant differences between these two classes of families were found.

The energy distribution for 4 centers of highest energy in superfamilies suggests that we are observing the fragmentation part of the spectrum of created particles, which is not considerably modified by the cascade and by the processes inside the chamber. It suggests also that the highest energy objects of most of the superfamilies were created in a single act of interaction at a relatively small altitude, probably about 2 km above a chamber [12].

General analysis of the nuclear-electromagnetic cascades, supported by model simulations of [13], shows that alignment should appear due to the interaction with pronounced coplanarity not far from a chamber, since development of the nuclear-electromagnetic cascade “blurs” the alignment after few interactions.

Assuming the most probable interaction altitude $H = 2$ km and measuring the distance between aligned cores, the momentum $p_t$ transferred between a core and the center of a 4 core jet (or group) is estimated as $p_t \sim 1$ GeV. A typical momentum of a core $p_t^\perp$ transverse to the axis of alignment is 10 times less, i.e. $< p_t > \sim 0.1$ GeV.
Average invariant mass $M$ of the entire subfamily of 4 aligned particles is $\langle M^2 \rangle = (60^{+120}_{-60})$ GeV$^2$.

It is difficult to explain coplanarity of secondaries within conventional models of interaction. Muhamedshin and Slavatinsky [13] have shown that the magnetic field of the Earth could not be responsible for any appreciable asymmetry. I. Royzen [14] has suggested to interpret the phenomenon of alignment as a projection of rupture of the quark-gluon string produced in the process of hard double inelastic diffraction dissociation, the string being inclined between a semi-hard scattered fast quark and the incident hadron remnants. Such explanation seems plausible because the energy threshold of the alignment effect is suitable for hard double inelastic diffraction. In this case a target diagram of a superfamily with alignment may be considered as a direct ‘photographic image of such process.

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

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