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Anisotropic and alignment effects in STRANA superfamily with $E_0 > 10^{16}$ eV

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Abstract: The striking alignment effect detected earlier in gamma-hadron stratospheric STRANA superfamily is supplemented here by analysis of the arrangement of all particles in the central area of the family. It showed the evident anisotropy in the lateral distribution of these particles confirming a coplanar scatter effect in the interaction.

Introduction

In 1975 in the emulsion balloon experiment at 30 km altitude there was detected a unique CR gamma-hadron family with energy > 10^{16} eV [1]. That event named STRANA is the result of a single nuclear interaction of primary CR particle since according to observation conditions in stratosphere there is negligible possibility for cascade development. This feature distinguishes the STRANA superfamily from the CR events detected lower in the atmosphere.
In stratospheric experiments there were detected only 2 events of so high energy: the gamma superfamily in Concorde experiment [2] and this gamma-hadron superfamily STRANA.
In mountain X-ray emulsion chambers there were detected at $E_0 > 10^{16}$ eV such phenomena as halo (a large diffuse spot in a family center) [3] and alignment of most energetic objects along straight line in a film plane [4]. Such features were found also in the STRANA superfamily, the event without cascade process influence. Here is presented additional information about anisotropy in the superfamily.

Experiment

Balloon flights with emulsion chambers aboard were carried out at 30 km altitude along the route Kamchatka peninsula – Volga river. Duration of a flight was around 160 hours. Flight altitude corresponds to 10 g/cm^2 of air. Multilayer emulsion chamber (Figure 1) with area 40x50 cm^2 consisted of 3 main blocks: target, spacer and calorimeter.
The chamber was designed first of all for primary CR registration. The target consisted of 90 plastic layers of 1.5 mm thickness interlayered with nuclear emulsion plates (200 mkm of plastic and 50 mkm of emulsion).
The target is necessary for primary detection and determination of its charge by track appearance in nuclear emulsion. The spacer designed for secondary divergence after an interaction consisted of 10 plastic layers of 5mm thickness interlayered with nuclear emulsion plates. Total thickness of target and spacer is equivalent to 0.5 c.u. or 0.3 nuclear interaction length for proton. The calorimeter was constructed of 9 lead layer of 0.5 thickness interlayered with nuclear emulsion and X-ray films. Total thickness of the calorimeter corresponds to 9 c.u. or 0.26 nuclear interaction length. Electron-photon cascades from gamma quanta and hadrons develop in lead plates of calorimeter and are detected in X-ray films as dark spots by which particle energy is determined.

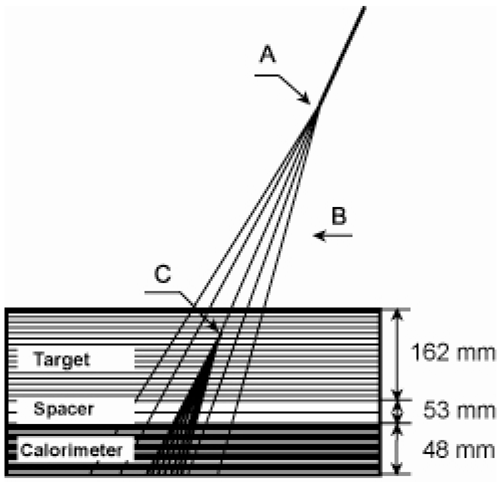

Figure 1: The construction of balloon born emulsion chamber and the scheme of STRANA superfamily detection. A — the interaction of primary particle, B — secondary particles of air gamma-hadron superfamily, C — the interaction of the leading particle within chamber.

General characteristics

The gamma-hadron family consists of 107 particles incident upon the chamber and detected by calorimeter: 76 electromagnetic particles (further mentioned as gamma-quanta) with total energy $\Sigma E\gamma \approx 1400$ TeV and 30 hadrons with total energy $\Sigma E_h^0 \approx 2500$ TeV (without the leading particle). Zenith angle of the family incidence is $\theta = 30^o$, that makes registration depth equal to 11.5 g/cm^2.

Because of restricted chamber depth the efficiency of hadron detection in this installation is around 40%. About 30% of particles is missed because the event fell not far from chamber edge. Taking into account these corrections the total energy becomes $\approx 9.2\times10^{15}$ eV.

High energy leading particle interacted repeatedly in 12-th layer of target block (see Figure1). As a result a narrow bunch of secondaries detected as tracks in nuclear emulsion developed fast in the matter of target and spacer and produced a large dark spot (halo) in X-ray films of the calorimeter. By recent estimation the leading particle energy is around $(1 \div 2)\times10^{15}$ eV. Thus the primary energy is estimated as $(1 \div 2)\times10^{16}$ eV.

Alignment effect

In this superfamily there was detected such interesting phenomenon as alignment. This effect is the consequence of coplanar scatter of secondaries in the nuclear interaction. As a result the most energetic objects in gamma-hadron families are aligned along a straight line in normal plane. According to Pamir Collaboration data the phenomenon appeared at $E_0 \approx 10^{16}$ eV. For quantitative description of the effect the parameter λ is used [5]:

$$\lambda_N = \frac{\sum_{i \neq j \neq k}^{N} \cos(2\varphi_{i,j,k})}{N(N-1)(N-2)},$$

where i,j,k — analyzed objects, $\varphi_{i,j,k}$ — the angle between vectors $\overline{ki}$ и $\overline{kj}$; N — the number of objects under analysis. λ_N comes to 1 in the case of ideal alignment, and comes to $-1/(N-1)$ in the case of isotropic disposition of points. An event is considered as aligned one, if $\lambda_N \geq 0.8$.

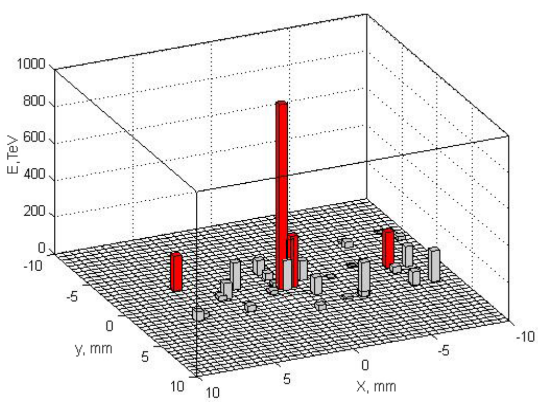

Figure 2: Particle diagram of the central area of the STRANA superfamily. Colored columns stand for 5 most energetic objects, in the very center there are 3 hadrons.

In the STRANA superfamily λ appeared to be for 3 most energetic objects $\lambda_3 = 0.98$, for 4 ones $\lambda_4 = 0.99$, for 5 ones $\lambda_5 = 0.90$ (see Figure2). It is rather high degree of alignment, that is not strange in a "pure" high energy event.

For estimation of probability of accidental occurrence of such single event with so high λ values

for 3, 4 and 5 objects there were performed special calculations with use of modern generator QGSJET (10000 simulated events for every primary type). The model QGSJET has no special mechanism for coplanar scatter of particles. Such combined probability to obtain an event with $\lambda_3 \geq 0.98$, $\lambda_4 \geq 0.99$, $\lambda_5 \geq 0.90$ is 0.01% for simulated families from primary proton and is 0.03% for simulated events from primary Fe nucleus.
It is worth to note, that 6 most energetic objects in the STRANA superfamily are of hadronic origin. Thus here one can see not the alignment of gamma-quanta or the alignment of multicore halos like in majority of first Pamir studies, but the alignment of hadrons. The most energetic hadron produced here a small halo in X-ray films. Besides, it is worth to note, that in Figure 2 there is evident anisotropy in the disposition of all particles in the central area of the superfamily. It is not related to the cut of family area by the film edge, since the edge is farther than 10 mm from the center of the superfamily. For alignment analysis here is considered only central area containing all high energy particles of the family. If whole family is under consideration, then 15 of 107 its particles are situated near alignment line. These 15 particles carry more than half of E_0.
Therefore the STRANA superfamily central part was analysed with other criteria of lateral anisotropy used in CR and high energy physics.

Other parameters of anisotropy

Let us characterize in brief other criteria used here.

Parameter α.
In [6] there was introduced the anisotropy parameter α popular in Pamir Collaboration:

$$\alpha_m = \frac{\sum_{i \neq j}^{m} \cos(2\varphi_{i,j})}{m(m-1)},$$

where $\varphi_{i,j}$ — an angle between i- and j-particle with vertex in the center of the event; m — number of particles. The parameter varies from 1 (for m points disposed in straight line) up to $\alpha_m \approx -1/(m-1)$ in isotropic case. Particular feature of α is the usage of energy weighted center for angular counting out, that is depending on energy determination accuracy.
Therefore α values may have large fluctuations relating to event center determination. Other its disadvantage is its invariance to independent shift of separate pairs of points along straight lines connecting these points and crossing the central point.

Parameter B
Criterion B introduced in [7] is an analogue of values used in accelerator experiments for separation of QCD jets.

$$B = 1 - b = 1 - \left\{ \frac{\sum E_i y_i^2}{\sum E_i x_i^2} \right\}$$

Here coordinates x, y are reduced coordinates, that is the axis x course is selected to obtain maximal B value (axis x extends along the direction of a family elongation).
At B=1 all particles are in a straight line, at B=0 particles are disposed isotropically. The value $B \in [0,1]$ depends significantly on event multiplicity and in its distribution coplanar events are sometimes overshadowed by background. This parameter may be regarded as sensitive to the very anisotropic events.

Parameter T'
Criterion T' as well as B is an analogue of the value "thrust" used in accelerator experiments for allocation of QCD jets.
In every family the direction with maximal T' has to be found. At T'=1 family particles are disposed isotropically, at $T' = \infty$ the particles drop along straight line.

$$T' = \left\{ \frac{\sum [\xi_i \cos\psi]}{\sum [\xi_i \sin\psi]} \right\},$$

where $$\xi_{ij} = \frac{E_i E_j}{E_i + E_j} R_{ij}$$

ψ — azimuthal angle between selected direction and vector !!! $\vec{R}_{ij}$; R_{ij} — distance between particles; E_i, E_j — particle energies.

Analysis in Pamir collaboration showed that $T' \in [1, \infty]$ may have large fluctuations due to its sensitivity to particles accidentally jumped aside from main group, since summation is carried out over all pairs of the particles.

Parameter r

Criterion r [8] can be used as an anisotropy parameter too. Coefficient of linear correlation r can be described in following way:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\left[\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2\right]^{1/2}}$$

where x_i, y_i, $\bar{x}$, $\bar{y}$ — particles coordinates and their average values. At $r=0$ particles are situated isotropically, at $r=1$ particles are disposed in straight line.

In our experiment the values of above mentioned anisotropy parameters were calculated for 33 particles in the central area of the family (see Figure 2) situated in the circle with 10 mm radius. The same parameters were calculated for simulated events with $E_0 = 2{\cdot}10^{16}$ эВ from QGSJET generator. There only 33 particles close to a center in every family were taking into account.

Table 1. Values of anisotropy parameters for 33 particles in the central area of the STRANA superfamily and average values of same parameters for simulated events (QGSJET model).

Parameters		***α***	***B***	***T'***	***r***
Simulation for various primary nuclei	P	0,014 ± 0,001	0,86 ± 0,003	2,75 ± 0,006	0,0006 ± 0,0027
	He	0,013 ± 0,001	0,86 ± 0,003	2,70 ± 0,005	0,0009 ± 0,0024
	C	0,018 ± 0,001	0,86 ± 0,003	2,73 ± 0,006	0,0018 ± 0,0029
	Mg	0,018 ± 0,001	0,86 ± 0,003	2,68 ± 0,005	0,0012 ± 0,0030
	Fe	0,044 ± 0,001	0,86 ± 0,003	2,74 ± 0,007	0,0012 ± 0,0025
Experiment		**0,282**	**0,999**	**3,21**	**0,21**

From Table 1 it is seen that experimental values of all parameters overcome calculated model values and come far out of possible fluctuations, that confirm the evident anisotropy of all particles in the central area of the STRANA superfamily.

The direction of elongation of this particle ensemble coincide with alignment of 5 most energetic hadrons, that means while emission these secondaries were distributed close to the coplanar scatter plane.

Conclusion

Analyzing the unique stratospheric gamma-hadron family with $E_0 > 10^{16}$ eV one can see features unobserved at lower energy. Those are an evident anisotropy and striking alignment of most energetic particles along a straight line in the central part of the superfamily.

For the first time at so high energy the phenomenon of coplanar scatter is detected in pure nuclear interaction without cascade distortions in atmosphere.

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