Coplanar Production of Pions at Energies above 10 PeV According to Pamir Experiment Data

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Abstract

Phenomenon of coplanar emission of secondary particles in superhigh energy nuclear interactions is investigated through the study of structure of $\gamma-$ray families detected in *Pamir* emulsion chamber experiment. To increase sensitivity of $\gamma-$family structure to anisotropy of the interaction predominantly contributing to the observed family, decascading of electromagnetic cascades into initial $\gamma-$rays and their subsequent coupling in π^0-mesons were performed. The probability to observe super energy families with aligned multi-core structures composed of 4 or 5 highest energy reconstructed neutral pions is higher than that predicted in *QGSJet* model by 3.5 standard deviations. The energy-lateral characteristics of the aligned multi-core pion structures favors the hypothesis of high p_T production of coplanar pions ($p_T \sim 3$ TeV/c). The estimated energy threshold for production of coplanar events is as high as $E_0 \sim 8$ PeV.

1. Introduction

The phenomenon of alignment of high energy particles in superfamilies was first observed in *Pamir* Experiment through the study of multi-core halo events [1]. The halo cores show strong tendency to be aligned along some straight line at target plane. Soon it was established that this phenomenon manifests itself through alignment of various high energy cores inside $\gamma - h-$families represented not only by halo cores but also by high energy $\gamma-$rays, hadrons and hadronic clusters [2, 3, 4]. The further study of characteristics of aligned events and simulation of various conventional physical processes which influence the development of nuclear-electromagnetic cascade in the atmosphere revealed the non-trivial nature of the observed phenomenon. The similar but single events were observed in some other cosmic ray experiments with XREC exposed both at mountain elevation [6, 7] and in the stratosphere [5].

The total world array of the experimental data, although rather poor due to low statistic of recorded superfamilies, favors the hypothesis of coplanar emission of high energy hadrons at super high energies ($E_0^{th} \sim 10$ PeV) resulting in

pp. 85–88

alignment of high energy cores of superfamilies at the observation level. Still there is no adequate theoretical explanation of the alignment phenomenon until now.

2. Experimental Data, Methods and Results of Analysis

For the present analysis, we selected only $\gamma-$families detected by various types of XREC exposed in *Pamir* experiment, namely, by thin Γ-block, deep C-chambers with carbon block and uniform lead Pb-chambers. The discrimination of hadron component enables us to avoid the problem of unification of reference frames used for determination of track coordinates for γ-rays and hadrons which are detected in different layers of XREC and thus to use the whole available experimental statistic. The total number of $\gamma-$families with $\sum E_\gamma \geq 100$ TeV ($E_\gamma \geq 4$ TeV, $R_\gamma \leq 15$ cm) selected and processed under the same conditions is 974 events and 62 of them are in energy range $\sum E_\gamma = 700 - 2000$ TeV.

To search aligned structures formed by N cores we use the earlier introduced criterion $\lambda_N = \sum\limits_{i\neq j\neq k} \cos 2\varphi_{ij}^k/(N(N-1)(N-2))$, where φ_{ij}^k is the angle between straight lines connecting ith and jth cores with kth core [2]. Quantity λ_N increases from $-1/(N-1)$ in the case of isotropic location of cores on the plane to 1 at complete alignment of N points along a single straight line. We consider 4-core structures with $\lambda_4 \geq 0.8$ to be aligned.

If one assumes that the alignment of high energy cores in superfamilies occurs as a result of coplanar production of high energy hadrons in nuclear interactions at super high energies, an efficiency of its observation should decrease with nuclear-electromagnetic cascade development due to three NEC conventional processes, i.e., successive interactions (3–6) of secondary hadrons with air nuclei, electro-magnetic decay of neutral pions into pairs of $\gamma-$rays which initiate electron-photon cascades (EPhC) in the atmosphere.

Previously, we reported [4, 8] that treatment of so-called nuclear or hadronic clusters increases sensitivity to the alignment manifestation due to effective reconstruction of hadrons (h^*) from the last but one generation of nuclear cascade in the atmosphere by means of clusterization procedure. To extract clusters in families, a parameter χ_{ij} is used with $\chi_c = 48$ TeV$\cdot$ cm for critical value.

The fraction of superfamilies ($\sum E_\gamma = 700 - 2000$ TeV) with aligned 4-core structures composed of highest energy clusters ($E_c \geq 10$ TeV) is as high as $F_{\lambda_4\geq 0.8}^{EXP} = 0.16\pm0.05$ to be compared with a background value $F_{\lambda_4\geq 0.8}^{MC0} = 0.05\pm0.01$ presented by the MC0 Monte Carlo code (analogue to QGSJet), which is based on QGS model of strong interactions and accounts for QCD-jet production [9].

The similar but even more strong effect of increase of alignment observation efficiency is attained by treating reconstructed neutral pions π^{0*} produced in the last nuclear interaction just above the chamber (Table 1). The dissection of simulated families reveals [8] that they can be effectively reconstructed by

Table 1. Fraction of aligned 4- and 5-core structures composed of reconstructed particles ($E_c^{th} = 10$ TeV)

Type of reconstructed particles		π^{0*} ($z_c = 3.4$ TeV·cm)	h^* ($\chi_c = 48.$ TeV·cm)
EXP	$F(\lambda_4^c \geq .8)$	$0.22 \pm .05$	$0.16 \pm .05$
$N_c = 4$	$< R_c >_4$ /cm/	1.3 ± 0.3	1.8 ± 0.5
MC0	$F(\lambda_4^c \geq .8)$	$0.07 \pm .01$	$0.05 \pm .01$
$N_c = 4$	$< R_c >_4$ /cm/	0.8 ± 0.2	0.6 ± 0.1
EXP	$F(\lambda_5^c \geq .8)$	$0.14 \pm .04$	$0.06 \pm .04$
$N_c = 5$	$< R_c >_4$ /cm/	1.3 ± 0.3	1.8 ± 0.5
MC0	$F(\lambda_5^c \geq .8)$	$0.01 \pm .01$	0.
$N_c = 5$	$< R_c >_4$ /cm/	0.8 ± 0.2	0.6 ± 0.1

means of so-called decascading procedure which successively couples neighboring gammas with parameter $z_{ik} = \frac{E_i E_k}{E_i + E_k} r_{ik} \leq z_c = 3.4$ TeV·cm, where E_i is the energy of unified gammas and r_{ik} is their mutual distance. It is important to note that number of events (13) containing aligned neutral pions is ~ 1.6 times greater than that of superfamilies with alinged 4-core cluster structures (8 events) and we have 5 additional aligned *'pure'* superfamilies. It means that almost 40% of aligned events are represented by events formed by one nuclear interaction predominantly contributing to the family.

As can be seen from Table 1, experimental superfamilies exhibits the alignment of not only 4-core structures but 5-core structures as well.

3. Specific Features of Aligned Events

Analysis of simulated events calculated in MC0 code revealed a strong correlation between the number N_{π^0} of high energy neutral pions ($E_c > 10$ TeV) and the energy E_0 of primary particles and particularly that of light nuclei ($A = 1 \div 16$). This behavior greatly differs from weak dependence of E_0 on $\gamma-$family energy $\sum E_\gamma$ and enabled us to estimate the energy threshold for coplanar production of hadrons. Fig. 1 shows that, at 84% confidence level, the coplanar events are observed if the primary proton energy $E_0 \geq 8$ PeV.

A distinguishing feature of aligned experimental $\gamma-$ families as compared with non-aligned ones is the significant difference in mean zenith angle θ of primary particles, namely, $< \cos\theta >= 0.968 \pm 0.009$ for aligned events ($\lambda_4^c \geq 0.8$) while for non-aligned ones $< \cos\theta >= 0.923 \pm 0.015$. This difference testifies that the observed aligned structures are produced predominantly in the first NEC interaction since inclined showers does not effectively preserve the aligned structures due to larger number of contributing successive interactions. Besides, the aligned

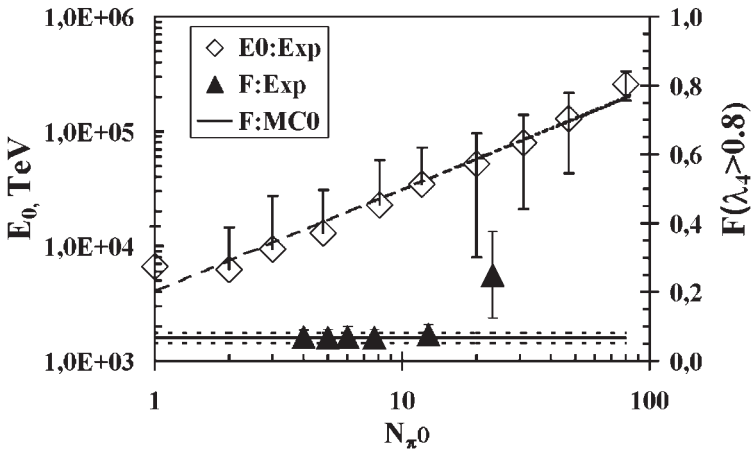

Fig. 1. Dependence of primary cosmic ray particle energy E_0 and fraction $F(\lambda_4^c \geq 0.8)$ of $\gamma-$ families with aligned four highest energy neutral pions on total number N_{π^0} of extracted pions with $E_c > 10$ TeV.

$\gamma-$families distinguishes by comparatively large spatial sizes of aligned structures composed of four highest energy nuclear clusters. The average radius of experimental aligned structures $< R_c^{(4)} >^{EXP} = 1.8 \pm 0.5$ cm is about three times higher than that given by the MC0-model simulation, i.e., $< R_c^{(4)} >^{MC0} = 0.6 \pm 0.1$ cm which is in agreement with experimental value for non-aligned events.

4. Conclusions

a) The alignment of superfamilies results from some new physical mechanism of coplanar emission of particles in strong interactions.

b) The coplanar emission of high-energy particles characterizes by a sharp energy threshold at $E_0^{th} \sim 8$ PeV and a large transverse momentum of about several GeV/c.

5. References

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