Theoretical Approach to Alignment Phenomenon

I. Royzen

P.N. Lebedev Physical Institute of Russian Academy of Sciences
53 Leninsky Prospect, 117924 Moscow, Russia

Abstract

An explanation of the puzzling alignment effect observed in cosmic ray experiments is suggested.

Few years ago the observation has been made [1] in cosmic ray experiments that the alignment of the main energy fluxes along a straight line in target (transverse) plane exceeds significantly the background level. More precisely, at superhigh energies of initial particle ($E_0 \geq 10^4$ TeV) the secondary particle superfamilies detected by deep lead X-ray emulsion chamber appeared to be situated almost along straight line in target plane (Fig.1). The coplanar scattering of such a type was so surprising that an attempt has been made to revise the result but instead they were confirmed with much better confidence level [2]. The analysis of the alignment effect for 74 high energy $\gamma$-families induced by hadrons above and within the chamber has been carried out. Their energies are selected to be $\sum E_{\gamma} = 100 \div 5000$ TeV (hadron energies being restored, accounting that the energy of induced $\gamma$-family is about 1/3 of the hadron energy it is originated from). This analysis suggested that superfamily production happened predominantly rather low above the chamber (at the altitude $H \simeq 2$km, since it seemed that nuclear-electromagnetic cascade development would blur alignment, if several interactions contributed). It confirmed a coplanar scattering and scaling-like fragmentation spectrum of energy distinguished cores. The alignment parameter $\lambda$,

$$-0.5 \leq \lambda = \frac{\sum_{i\neq j\neq k}^{m} \cos(2\phi_{ijk})}{m(m-1)(m-2)} \leq 1,$$
is used as the alignment criterion where \( m \) stands for a number of centers of highest energy and \( \phi_{ijk} \) is the angle between the two-dimensional vectors \( \vec{k}_i \) and \( \vec{k}_j \) in target plane, an event being recognized to have alignment, if \( \lambda \geq 0.6 \). Actually, events with \( m = 4 \) were chosen only because of too high statistical background for \( m = 3 \) and rather poor statistics for \( m \geq 5 \). The threshold-like behavior of the effect has been observed: no alignment at \( \gamma \)-family energies \( \sum E_\gamma \leq 100 \text{ TeV} \), then its gradual increase within energy range \( 100 \text{ TeV} \leq \sum E_\gamma \leq 500 \text{ TeV} \) to manifest itself finally in (20-40)% of total number of events. 14 events with \( \sum E_\gamma \geq 500 \text{ TeV} \) have been observed, exhibiting most striking alignment structure (\( \lambda \geq 0.8 \)). Core transverse momentum \( p_T \) was estimated by rough relation \( p_T H \simeq E_0 R \), \( R \) being the distance of a spot from the interaction axis. The mean ratio of value of maximal relative core transverse momentum to its normal to the alignment line projection (in target plane) \( k_T \) is \( \langle p_T \rangle / \langle k_T \rangle \simeq 10 \). No other peculiarities of alignment events compared to ”usual” cascade have been noticed.

The first attempt of theoretical consideration of the above alignment phenomenon has been made by F. Halzen and D.A. Morris [3], whose approach was based on the assumption that semihard gluon jets is a feature of all events at energies above \( 10^4 \) TeV. It was shown that within this approach the cosmic ray observations were associated probably with the jet alignment in three-jet events observed already in the collider experiment [4].

I would like to suggest an alternative treatment which makes it possible to understand many features of cosmic ray alignment observations quite naturally, including the threshold-like energy behavior and fraction in extensive atmospheric showers as well as the typical projections of core transverse momenta to the alignment line and normal to it, and allowing for events with more, than four cores aligned, that have been extracted recently from cosmic ray data [5]. The main point of the approach under consideration is that the alignment events are assumed to be associated with semihard double inelastic diffraction (SHDID) of hadrons [6]. Let us trace them step-by-step.

## 1 Total cross section of SHDID.

In the accordance with the conventional Regge-Gribov approach, the one-Pomeron contribution to the differential cross section of SHDID can be ex-
pressed at \( s \gg M_{1,2}^2 \gg Q_T^2 \gg 1 \text{ GeV}^2 \) in the form:

\[
\frac{d\sigma^0_{DD}}{dQ_T^2} = \frac{\sigma_t r^2(Q_T^2)}{16\pi} \int_{Q_T^2/\epsilon}^{s \epsilon} \frac{dM_1^2}{M_1^2} \int_{Q_T^2/\epsilon}^{sQ_T^2/M_1^2} \frac{dM_2^2}{M_2^2} \left( 2 \frac{sQ_T^2}{M_1^2 M_2^2} \right)^{2(\alpha_P - 1)}
\]

(1)

where \( \sqrt{s}, \sigma_t, Q_T, M_1 \) and \( M_2 \) are CMS total interaction energy, total cross section, transverse momentum transferred, and invariant masses of final diffractively excited states respectively, \( r(Q_T^2) \) is three-Pomeron vertex and \( \alpha_P \equiv \alpha_P(Q_T^2) \) is the Pomeron trajectory; the parameter \( \epsilon = \max(M_{1,2}^2/s) \simeq 0.05 \) is to be chosen to single out diffraction processes from other ones [7]. Since the mean slope of the Pomeron trajectory is the only dimensional parameter which can be responsible for the decrease of the function \( r(Q_T^2) \) as \( Q^2 \) is increased, the domain where \( r(Q_T^2) \) is expected to be nearly constant is estimated as \( Q_T^2 \leq (\alpha_P')^{-1} \) where \( \alpha_P' \) is an effective mean value of the derivative \( \alpha_P' \) there which is reasonably evaluated to be \( \alpha_P' \leq (0.1 - 0.2) \text{ GeV}^{-2} \). It is why this domain is expected to be remarkably large, from \( Q_T^2 = 0 \) to \( Q_T^2 \simeq 10 \text{ GeV}^2 \) or even larger (it has been observed long ago by comparison of the elastic and single inelastic diffraction differential cross sections that \( r(Q_T^2) \simeq \text{const} \) at \( Q_T^2 \leq 1.5 \text{ GeV}^2 \) [7], wherefrom, in particular, a rather slow \( Q_T \)-dependence of double inelastic diffraction differential cross section at \( Q_T^2 \leq 1.5 \text{ GeV}^2 \) follows). The double inelastic diffraction is the only type of hadron interaction which is expected to exhibit such slow transverse momentum dependence. At still larger values of squared 4-momentum transferred Pomeron is expected to be dissolved to its constituents [6] that begin to interact independently, so that the ”normal” QCD regime \( \frac{\alpha_S^2}{Q^{-4}} \) is to be approached gradually. In what follows the logarithmic dependence on \( Q_T \) and rather ambiguous but definitely slow decrease of \( \alpha_P(Q_T^2) \) in the right-hand side of eq.(1) are accounted on the average as \( Q_T^2 \rightarrow Q_T^2/2 \) and \( \alpha_P(k_T^2) \rightarrow \alpha_P(k_T^2/2) \). The rough estimate of screening corrections to the one-Pomeron SHDID scattering amplitude \( A_{DD}^0 \) associated with diagrams depicted in Fig.3 shows that

\[
A_{DD} \simeq \frac{A_{DD}^0}{1 + 2\frac{\sigma_t}{\sigma_t}}
\]

(2)
$A_{DD}$ being the corrected amplitude. It is reasonable to adopt $\sigma_{el}/\sigma_{t} \simeq 0.2$ and enhance the above correction (i.e., to multiply the denominator in eq.(2)) by the phenomenologically approved (for forward elastic scattering amplitude) factor about 1.5, accounting the shadowing by the inelastic intermediate states. Then the corrected SHDID amplitude is expected to be $A_{DD} \simeq 0.55A_{DD}^0$ and the corresponding differential cross section is

$$\frac{d\sigma_{DD}}{dk^2_T} \simeq 0.3\frac{d\sigma_{DD}^0}{dk^2_T}.$$  

After integration of eq.(1) over the region $Q^2_T \leq (\overline{\alpha_P})^{-1}$ one obtains the total cross section of SHDID

$$\sigma_{DD} \simeq \frac{0.3}{128\pi\overline{\alpha_P}^2(1 - \overline{\alpha_P})} \ln(\overline{\alpha_P}^2s)$$  

If one chooses a reasonable values $\overline{\alpha_P} \simeq 0.5$, $\overline{\alpha_P} \simeq 0.15$ GeV$^{-2}$ and the experimental value of $r_0$, $r_0 \simeq 0.8$ GeV$^{-1}$, then the fraction of SHDID is expected to be $\sigma_{DD}/\sigma_{t} \simeq 0.04; 0.07; \text{ and } 0.10$ at $s = 10^5; 10^6$ and $10^7$ GeV$^2$ respectively. It can be several times less or larger, since the above estimate is rather rough, but its smooth logarithmic threshold-like energy increase is independent of the choice of parameters.

2 Transverse (target) plane structure of events.

It seems reasonable to expect that hadronization of diffractively excited final states produced by SHDID is dominated by mechanism of string rupture as shown in Fig.4, string been formed between scattered colored hadron constituent (quark, diquark or gluon) and remnant of the same hadron. Any alternative string configuration would be unfavorable since it implies formation of some strings of a very high energy (it is worthy to mention that diffractively produced state associated with target particle was always out of the game in cosmic ray experiments under discussion because it is never seen within the area of observation; it is why the projectile inelastic diffraction only is thought of throughout the paper). At the same time, transferred momentum $Q_T \simeq 3$ GeV is insufficiently large for the fragmentation mechanism of hadronization to prevail. Let us consider the above string in its own CMS
and adopt that secondary particle rapidity and transverse momentum distributions in Pomeron-proton interaction is similar to that in real hadron one at CMS energy $M_1$ ($or M_2$) (as to the rapidity distribution, it is supported by the well known result of UA4 Collaboration [8]). Since what is observed is nothing else, than transverse plane projection of the picture which is resulted from its rupture, it becomes obvious that the typical ratio of a secondary transverse momentum projection normal to reaction plane (i.e., to the plane of draft) to ”transverse momentum string length” (i.e. to LS relative transverse momentum of leading particles oppositely directed in string CMS ) is about $\frac{k_T \sqrt{2}}{Q_T}$ where $< k_T > \simeq 300 \text{MeV}$ is mean transverse momentum of secondaries in hadron interactions , and mean leading particle energy is experimentally proved to be about half of incident particle one. At $Q_T \simeq 3 \text{GeV}$ this ratio is about 0.13.

3 Comparison to the experimental data.

The only point what remains to be discussed to compare the above consideration to the experimental data is an obvious estimate of the role of atmospheric cascade. Since the atmosphere thickness above the altitude where the calorimeter is mounted corresponds to about 3.5 nuclear mean free paths, the probability of at least one SHDID collision is about $1 - (1 - \frac{\sigma_{DD}}{\sigma_T})^{3.5} \simeq 0.3$ at $s = 10^7 \text{ GeV}^2$. If it does happen, then the subsequent soft collisions can not, most probably, blur essentially the target plane picture it initiates, especially for energy distinguished cores. It is why the additional assumption suggested by experimenters [2] seems to be not necessary, that alignment is caused by some peculiarities of the lowest nuclear collision above the chamber only. At the same time, the threshold-like dependence of alignment on core energies is associated, may be, with the violating role of nuclear cascade. Thus, the main puzzling experimental features of alignment phenomenon, namely, the fraction of alignment events about (20-40)\% and the ratio of mean value of normal to reaction plane projection of core transverse momentum to maximal value of core relative transverse momenta ($\simeq 0.1$) (string ”half-thickness” to its ”length” in transverse momentum space) are compatible qualitatively with the above theoretical consideration (30\% and 0.13 respectively), if one adopts that each core is originated (due to electromagnetic cascade) from a hadron created along with string rupture. The threshold-like dependence of SHDID
cross section on interaction energy can elucidate why the phenomenon has not been noticed at lower energies (especially, accounting a poor statistics and other ambiguities of cosmic ray experiments). However, this point as well as some other features of the phenomenon, such as its threshold-like dependence on core energies, core energy distribution, their energy sequence along the alignment line, etc., needs both the enrichment of statistics and MC simulation of cascade and SHIDID collisions themselves (especially, accounting that hadrons of different masses can be produced at the end of string and along its length) which are in progress. Unfortunately, it is rather questionable, whether an attempt to observe the alignment phenomenon will be undertaken in accelerator experiments soon.

I would like to thank A. Capella, E. Feinberg, J. Tran Thanh Van, and especially A. Managadze for many fruitful discussions.

The work is supported, in part, by Russian Foundation for Fundamental Researches and International Science Foundation.
References

[1] Pamir collaboration, ”Analysis of structure of halo in families with energy $E_\gamma \geq 500\text{TeV}”$, Proceedings 5th International Symposium on Very High Energy Cosmic Ray Interactions, Lodz, 1988, v. Contributed Papers, p. 9.

[2] T.P. Amineva, G.F. Fedorova et al., ”Alignment of Increased Background Region in Gamma-Hadron Superfamilies”, Proceedings 6th International Symposium on Very High Energy Cosmic Ray Interactions, Tarbe, 1990 v. Contributed Papers, p. 264; I.P. Ivanenko, V.K. Kopenkin, A.K. Managadze and I.V. Rakobolskaya, Pisma JETF, 1992, v. 56, p. 192.

[3] F. Halzen and D.A. Morris, Phys. Rev., 1990, v. D42, p. 1435.

[4] UA1 Collaboration, G. Arnison et al., Phys. Lett., 1985, v.158B, p. 494

[5] A. Managadze, Private communication.

[6] A. Mironov and I. Royzen, Sov. Yad. Fiz., 1988, v. 47, p. 1125; v. 48, p. 194.

[7] A. Alberi and G. Goggi, Phys. Rep. 1984, v. 74, no. 1.

[8] UA4 Collaboration, D. Bernard et al., Phys. Lett., 1986, v. 166B, p.459
Figure captions

Fig.1. The example of target plane picture with energy distinguished cores for event with alignment, $\lambda = 0.95$; figures stand for energy in TeV (already multiplied by factor 3 for hadrons); and or stand for electromagnetic halo and hadrons of high energy respectively. Other particles of the family are marked as ($\gamma$-quanta) and (hadrons).

Fig.2. One-Pomeron exchange approximation to SHDID. Wavy lines refer to Pomeron exchange, $M_1$ and $M_2$ are invariant masses of diffractively excited states, $Q$ is 4-momentum transferred, $r$ is triple-Pomeron vertex function.

Fig.3. Typical diagrams, accounting screening corrections. Notation is the same as in Fig.2.

Fig.4. The scheme of final state hadronization by string rupture mechanism.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9503429v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/hep-ph/9503429v1