

# Cosmic rays and antishadowing

S. M. Troshin,\* N. E. Tyurin

*Institute for High Energy Physics,  
Protvino, Moscow Region, 142281, Russia*

## Abstract

We note that antishadowing could help in the explanation of cosmic rays regularities such as knee in the energetic spectrum and existence of penetrating and long-flying particles.

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\*email: [Sergey.Troshin@ihep.ru](mailto:Sergey.Troshin@ihep.ru)

Cosmic rays are the charged nuclei arriving from the outside of the solar system. The cosmic rays investigations are an important source of astrophysical information (cf. e.g. [1]) and simultaneously they provide a window to the future of accelerator studies<sup>1</sup>.

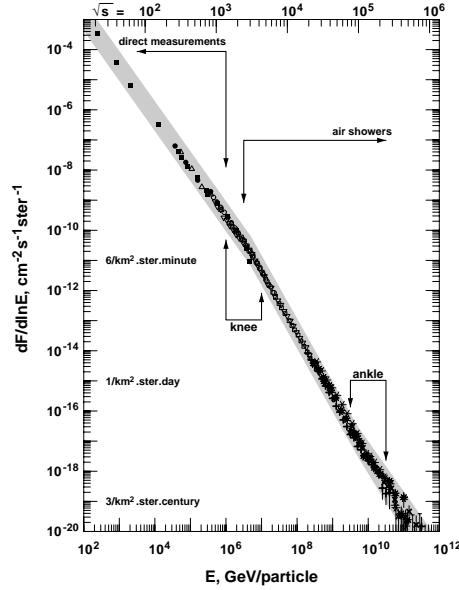


Figure 1: Energy spectrum of the cosmic rays, figure from the first reference of [3].

Investigations of cosmic rays give us a clue that the hadron interaction and mechanism of particle generation is changing in the region of  $\sqrt{s} = 3 - 6$  GeV[3, 4]. Indeed, the energy spectrum which follows simple power-like law  $F(E) = cE^{-\gamma}$  changes its slope in this energy region and becomes steeper: index  $\gamma$  increases from 2.7 to 3.1. It is important that the knee in the energy spectrum appears in the same energy region where the penetrating and long-flying particles also start to appear in the extended air showers (EAS): the absorption length is also changing from  $\lambda = 90 \text{ g/cm}^2$  to  $\lambda = 150 \text{ g/cm}^2$  (cf. [3]). There is also specific feature of the events at the energies beyond knee such as alignment. The above phenomena were interpreted as a result of appearance among the secondaries of the new particles which have a small inelastic cross-section and/or small inelasticity. These new particles can be associated with a manifestation of the supersymmetry, quark-gluon plasma formation and other new mechanisms.

<sup>1</sup>It should be noted however that the results for the total cross-section extracted from cosmic rays measurements significantly rely on particular model, because cosmic rays do not provide information on elastic scattering cross-section [2]

However, there is another possibility to treat those cosmic rays phenomena as the avatars of the antishadow scattering mode at such energies [5].

Unitarity of the scattering matrix  $SS^+ = 1$  implies, in principle, an existence at high energies  $s > s_0$ , where  $s_0$  is a threshold<sup>2</sup> of the new scattering mode – antishadow one. It has been revealed in [5] and described in some detail (cf. [6] and references therein) and the most important feature of this mode is the self-damping of the contribution from the inelastic channels.

Antishadowing leads to asymptotically dominating role of elastic scattering. The cross-section of inelastic processes rises with energy as  $\ln s$ , while elastic and total cross-sections behave asymptotically as  $\ln^2 s$ . The antishadow scattering mode could be definitely revealed at the LHC energies and the phenomena observed in the cosmic rays studies confirm it. Starting at some threshold energy  $s_0$  (where amplitude reaches the black disk limit at  $b = 0$ ), antishadowing can occur at higher energies in the limited region of impact parameters  $b < R(s)$  (while at large impact parameters only shadow scattering mode can be realized). Note that a shadow scattering mode can exist without antishadowing, but the opposite is not true.

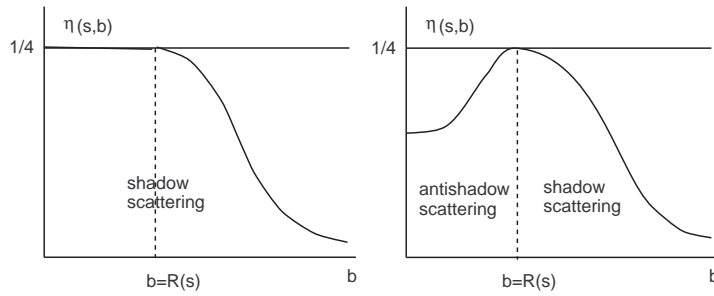


Figure 2: Impact parameter dependence of the inelastic overlap function in the standard unitarization scheme (left panel) and in the unitarization scheme with antishadowing (right panel).

The inelastic overlap function  $\eta(s, b)$  becomes peripheral when energy is beyond  $s = s_0$ . At such energies the inelastic overlap function reaches its maximum value at  $b = R(s)$  where  $R(s)$  is the interaction radius. So, beyond the transition energy

<sup>2</sup>Model estimates show that antishadow scattering mode starts to develop right beyond Tevatron energies, i.e.  $\sqrt{s_0} \simeq 2$  TeV[7]

range there are two regions in impact parameter space: the central region of anti-shadow scattering at  $b < R(s)$  and the peripheral region of shadow scattering at  $b > R(s)$ . The impact parameter dependence of the inelastic channel contribution  $\eta(s, b)$  at  $s > s_0$  are represented in Fig. 2 for the case of standard unitarization scheme and for the unitarization scheme with anishadowing.

At the energies  $s > s_0$  small impact parameter scattering is mostly elastic one. Thus head-on colliding particles will provide appearance of penetrating long-flying component in the EAS and such particles will spend only small part of their energy for the production of secondaries. The head-on collisions will lead to smaller number of secondary particle and it will provide faster decrease of the energy spectrum of cosmic rays, i.e. it will result in the appearance of the knee. This qualitative picture will be explained in more detail in what follows.

Antishadowing leads to suppression of particle production at small impact parameters, and the main contribution to the integral multiplicity  $\bar{n}(s)$

$$\bar{n}(s) = \frac{\int_0^\infty \bar{n}(s, b)\eta(s, b)bdb}{\int_0^\infty \eta(s, b)bdb} \quad (1)$$

comes from the region of  $b \sim R(s)$ .

Due to peripheral form of the inelastic overlap function the secondary particles will be mainly produced at impact parameters  $b \sim R(s)$  and this could lead to the events with alignment observed in cosmic rays and also to the imbalance between orbital angular momentum in the initial and final states since particles in the final state will carry out large orbital angular momentum. To compensate this orbital momentum spins of secondary particles should become lined up, i.e. the spins of the produced particles should demonstrate significant correlations when the antishadow scattering mode appears [8]. Thus, the observed phenomena of alignment in cosmic rays events and predicted spin correlations of final particles should have a common origin.

Antishadowing leads to the nonmonotonous energy dependence of gap survival probability [9]. The gap survival probability, namely the probability to keep away inelastic interactions which can result in filling up by hadrons the large rapidity gaps, reaches its minimal values at the Tevatron highest energy and this is due to the fact that the scattering at this energy is very close to the black disk limit at  $b = 0$  (Fig. 3). It is clear that its higher value means higher fraction for diffractive component and consequently the increasing of this component would result in the enhancement of the relative fraction of protons in the observed cosmic rays spectrum. Otherwise, decreasing of this quantity will lead to increase of pionization component and consequently to the increasing number of muons observed as multi-muon events. Experiment reveals that relative fraction of protons in cosmic rays also shows nonmonotonous energy dependence [10]. To explain such dependence an additional component is introduced *ad hoc* at the energies above  $3 \cdot 10^7$

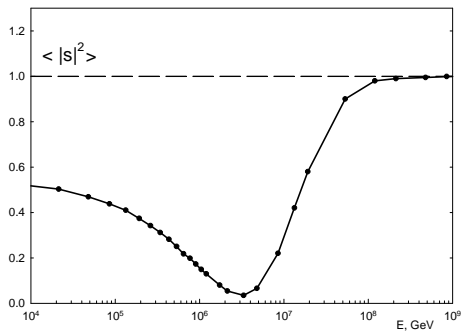


Figure 3: Energy dependence of gap survival probability.

GeV. It was shown that account of the antishadowing makes an introduction of this *ad hoc* component unnecessary.

The inelasticity parameter  $K$ , which is defined as ratio of the energy going to inelastic processes to the total energy, is important for the interpretation of the cosmic rays cascades developments. Its energy dependence is not clear and number of models predict the decreasing energy dependence while other models insist on the increasing energy behaviour at high energies (cf. e.g. [11]). Adopting simple ansatz of geometrical models where parameter of inelasticity is related to inelastic overlap function we can use the following equation for  $\langle K \rangle$  [12]

$$\langle K \rangle = 4 \frac{\sigma_{el}}{\sigma_{tot}} \left( 1 - \frac{\sigma_{el}}{\sigma_{tot}} \right)$$

to get a qualitative knowledge on the inelasticity energy dependence. The estimation of inelasticity based on the particular model with antishadowing [7] leads to increasing dependence of inelasticity with energy till  $E \simeq 4 \cdot 10^7$  GeV. In this region inelasticity reaches maximum value  $\langle K \rangle = 1$ , since  $\sigma_{el}/\sigma_{tot} = 1/2$  and then starts to decrease at the energies where this ratio goes beyond the black disk limit  $1/2$ . Such qualitative nonmonotonous energy dependence of inelasticity is the result of transition to the antishadowing scattering regime. It is worth noting that the maximum in inelasticity energy dependence is correlated with the minimum of the relative fraction of protons in the cosmic rays.

It should be noted that the behaviour of the ratio  $\sigma_{el}/\sigma_{tot}$  when it goes to unity at  $s \rightarrow \infty$  does not mean decreasing energy dependence of  $\sigma_{inel}$ . The inelastic cross-section  $\sigma_{inel}$  increases monotonically and it grows as  $\ln s$  at  $s \rightarrow \infty$ . Therefore the depth of shower maximum which is related to the probability of inelastic interactions would become shallower with energy. Its energy dependence is not affected by the dominating role of elastic scattering which occurs first at the small impact parameters.

The relation of the knee and other features observed in the cosmic rays measurements with the modification of particle generation mechanism is under discussion since the time of their discoveries. We would like to point out here one particular realization of such approach where the corresponding generation mechanism is strongly affected by unitarity effects and the energy region between knee and ankle is related to the transition region to the antishadow scattering mode, i.e. the real energy spectrum  $F_0(E)$  is modulated by the significant variation of the scattering matrix  $S$  in the energy region which starts at  $E_1 \simeq 10^5$  GeV and ends at  $E_2 \simeq 10^9$  GeV and this results in the regularities in the observed spectrum  $F(E)$ . Below the energy  $E_1$  and beyond the energy  $E_2$  variation of scattering matrix is slow and the primary energy spectrum  $F_0$  is not affected. This hypothesis is not only but would be one of the natural explanations of the observed cosmic rays regularities.

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