INDICATIONS FOR THE NEW UNITARITY REGIME IN THE EXTENSIVE AIR SHOWERS MEASUREMENTS

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We note that the new unitarity regime when scattering amplitude goes beyond the black disc limit (antishadowing) could help in the explanation of the regularities such as knee in the energy spectrum, existence of penetrating and long-flying particles and other features observed in the measurements of the extensive air showers which originate from cosmic particles interactions with the atmosphere.

Introduction – main experimental regularities

The experimental and theoretical studies of cosmic rays are the important source of astrophysical information [1] and they simultaneously provide a window to the future results of accelerator studies of hadron interaction mechanism at the LHC [1].

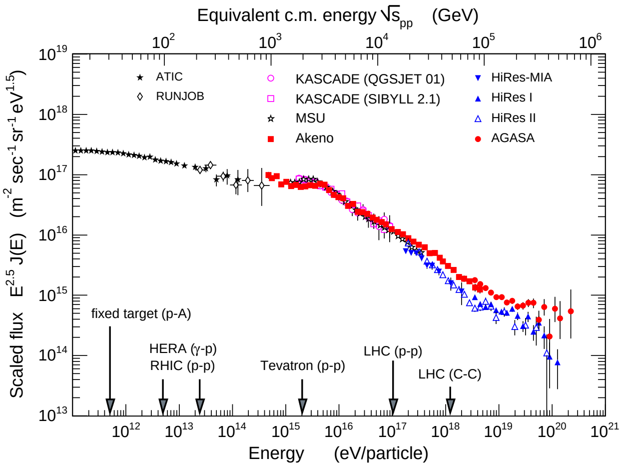

Fig. 1. Scaled energy spectrum of the cosmic rays, figure from [2].

It can happen that the investigations of cosmic rays will give us a clue that the hadron interaction and mechanism of particle generation is changing in the region of $\sqrt{s} = 3 - 6$ TeV [3, 4]. Indeed, the energy spectrum which follows simple power-like law $F(E) = cE^{-\gamma}$ changes its slope in this energy region (Fig. 1) and becomes steeper: index γ 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 extensive air showers (EAS): the absorbtion length is also changing from $\lambda = 90\ g/cm^2$ to $\lambda = 150\ g/cm^2$ [3]. There is also specific feature of the events at the energies beyond knee such as

[1]It should be noted that the value of the total cross–section extracted from cosmic rays measurements significantly depend on the particular model for elastic scattering, because measurements of the extensive air showers provide information on inelastic scattering cross–section only [2].

alignment [5] (and references therein). Studies of this phenomena in EAS can be related to coplanar QCD jets studies at accelerator energies [6]. The interpretation of the cosmic-ray data is complicated since the primary energies of cosmic particles are far beyond of the energies of modern accelerators with fixed targets and existing simulation programs directly extrapolate the present knowledge on the hadron interaction dynamics in the unknown energy region [7]. The above phenomena were interpreted as a result of appearance 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. In this note we would like to pursue another possibility and treat those cosmic rays phenomena observed in EAS as the manifestations of the new unitarity regime (antishadow scattering mode) at such high energies [8].

1 New unitarity regime in hadron interactions

Unitarity of the scattering matrix $SS^+ = 1$ implies, in principle, an existence of the new scattering mode — antishadow one — at high energies $s > s_{bd}$, where s_{bd} is a threshold [2]. It has been revealed in [8] and described in some detail [10] (and references therein) and the most important feature of this mode is the self-damping of the inelastic channels contributions at small values of impact parameter — antishadowing. The antishadowing leads to $P(s, b = 0) \to 1$ at $s \to \infty$, where P is a probability of the absence of the inelastic interactions, $P(s, b) \equiv |S(s, b)|^2$, where S is the elastic scattering S–matrix.

Self-damping of the inelastic channels 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 definitely be observed at the LHC energies and studies of the extensive air showers originated from the cosmic particles interactions with the atmosphere provide evidence for it as we will argue in what follows. Starting at some threshold energy s_{bd} (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).

The inelastic overlap function $\eta(s, b)$ becomes peripheral when energy goes beyond $s = s_{bd}$ (Fig. 2). At such energies the inelastic overlap function reaches its maximum value at $b = R(s)$, where $R(s)$ is the interaction radius, while the elastic scattering occurs at smaller values of impact parameter, i.e. $\langle b^2 \rangle_{el} < \langle b^2 \rangle_{inel}$. Note that

$$\langle b^2 \rangle_i = \frac{1}{\sigma_i} \int b^2 d\sigma_i \equiv \frac{1}{\sigma_i} \int_0^\infty b^2 \frac{d\sigma_i}{db^2} db^2,$$

where $i = tot, el, inel$ and

$$\mathrm{Im} f(s, b) \equiv \frac{1}{4\pi} \frac{d\sigma_{tot}}{db^2}; \ |f(s, b)|^2 \equiv \frac{1}{4\pi} \frac{d\sigma_{el}}{db^2}; \ \eta(s, b) \equiv \frac{1}{4\pi} \frac{d\sigma_{inel}}{db^2}$$

and unitarity condition in the impact parameter space is the following

$$\mathrm{Im} f(s, b) = |f(s, b)|^2 + \eta(s, b),$$

where $f(s, b)$ is the elastic scattering amplitude. The quantity $\langle b^2 \rangle$ is a measure of the reaction peripherality. Despite that the asymptotics for σ_{el} and σ_{inel} are different, the quantities $\langle b^2 \rangle_{el}$ and $\langle b^2 \rangle_{inel}$ have the same asymptotical energy dependence, proportional to $\ln^2 s$.

So, beyond the transition energy range there are two regions in impact parameter space: the central region where self-damping of inelastic channels occurs (antishadow scattering at $b < R(s)$) and the peripheral region of shadow scattering at $b > R(s)$.

At the energies $s \gg s_{bd}$ small impact parameter scattering is almost elastic one.

[2]Model estimates show that new scattering mode starts to develop right beyond Tevatron energies, i.e. at $\sqrt{s_{bd}} \simeq 2$ TeV [9], which corresponds to the energy in the laboratory system $E_{bd} \simeq 2\ PeV$.

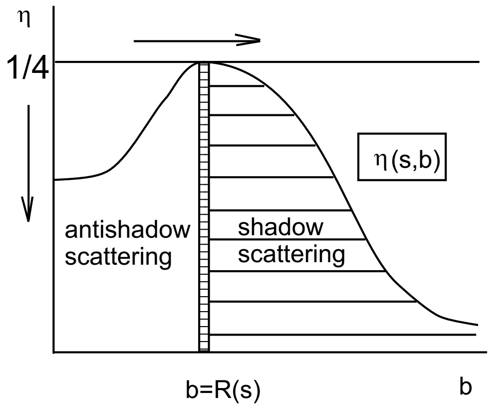

Fig. 2. Impact parameter dependence of the inelastic overlap function in the framework of the unitarization scheme with antishadowing. Arrows indicate the directions of movement of minimum at $b = 0$ and maximum at $b = R(s)$ with the energy increase. In the region of $b = R(s)$ the complete absorbtion takes place, i.e. $|S(s, b = R(s))|^2 = 0$.

2 Indications for the new unitarity regime in EAS

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 particles 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. It should be noted that this effect has a threshold in the energy dependence. It is also important to note that due to small probability of the sequential head-on collisions the number of events with penetrating particles also should be small. Nontheless, such events have been observed in the experiments PAMIR [11].

Antishadowing leads to suppression of particle production at small impact parameters:

$$\bar{n}(s) = \frac{1}{\sigma_{inel}(s)} \int_0^\infty \bar{n}(s,b) \frac{d\sigma_{inel}}{db^2} db^2, \tag{1}$$

i.e. multiplicity distribution

$$P_n(s,b) \equiv \frac{1}{\sigma_{inel}(s)} \frac{d\sigma_n(s)}{db^2}$$

and mean multiplicity $\bar{n}(s, b)$ in the impact parameter representation have no absorptive corrections, but peripherality of $d\sigma_{inel}/db^2$ (Fig. 1) leads to suppression of particle production at small impact parameters and the main contribution to the integral multiplicity $\bar{n}(s)$ comes from the region of $b \sim R(s)$ (Eq. (1)). Thus, the distinctive feature of this mechanism is the ring-like shape of particle production which will lead to correlations in the transverse momentum of the secondary particles. It means that the enhancement of particle production at fixed impact distances $b \sim R(s)$ would lead to higher probability of the circle events observed in the detectors. Such events would reflect the production geometry with complete absorbtion at the impact distances equal to the effective radius of interaction $R(s)$. Needless to say that the observation of such events is not an easy task due to the randomness of the multiple interaction of secondary particles in the atmosphere which would wipe out geometrical regularities. Only fragments of these particle circlular events produced in primary interaction could have a chance to survive passing the atmosphere and can mimic then prolongated events interpreted as the the events with alignment. Such events were observed in EAS in several experiments [12] with primary energies in the region $E_0 = 8-10\ PeV$. At the lower energies the probability to observe alignment is small and there should be no such phenomena at all at the energies where the new unitarity regime has not yet been developed. It is an important problem to separate dynamically generated alignment from a background random component [5] dominating at lower primary energies $E_0 = 1-3PeV$, where antishadowing is absent or just starts to develop.

The particle production from the distances of $b \sim R(s)$ would lead 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 [13]. Of course, such correlations would also be diluted by the randomness of secondary interactions.

Thus, the phenomena of dynamical alignment in EAS and predicted spin correlations of final particles have a common origin, i.e. the spins of particles in the events with alignment should be lined up. The model estimate for the primary energy when these phenomena should appear is $E_0 \gg E_{bd}$, where $E_{bd} \simeq 2\ PeV$ is the energy when the new unitarity regime starts to develop at small impact parameters. It would be interesting to measure parameter d_4^{max}, which describes distances between hadrons measured in detector, in the energy range $E_0 \sim 10\ PeV$ to reveal possible circular events substructures [3], since this parameter is more sensitive to transverse momentum of the secondary particles than the parameter λ_4 [5]. Its energy dependence in due to antishadowing would have $1/\ln E_0$ behaviour.

The detected particle composition of the EAS is closely related to the quantity known as the gap survival probability. The gap survival probability is the probability to keep away inelastic interactions which can result in filling up rapidity gaps by hadrons. Antishadowing leads to the nonmonotonous energy dependence of this quantity [15]. It reaches the minimal values at the highest Tevatron energy. 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).

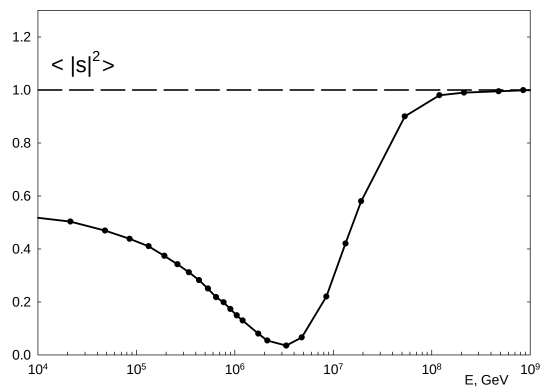

Fig. 3. Energy dependence of gap survival probability.

It is clear that the higher value of gap survival probability 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 ground-level 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.

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 EAS 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 [16]. Adopting simple ansatz of geometrical models where parameter of inelasticity is related to inelastic overlap function we can use the following equation for $\langle K\rangle$ [17]

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

to get a qualitative knowledge on the inelasticity energy dependence. The estimation of inelasticity based on the particular model with antishadowing [9] leads to increasing dependence of inelasticity with energy till

[3] Observation of the events with such substructures was reported in [14]

$E \simeq (3-4) \cdot 10^7$ 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. The distribution on the inelasticity is related to the distribution on the effective mass number, i.e. changes of A are equivalent to changes of $\langle K \rangle$, and, for example, high-inelasticity primary proton interaction produces the same result at the ground level as the low-inelasticity primary interaction of the heavy nuclei [18]. The available experimental data on the average logarithm of the effective nuclear mass number, extracted from the energy dependence of the depth of EAS maximum, have large error bars, but they also could indicate a nonmonotonous energy dependence with the maximum in the region $E_0 \simeq (3-4) \cdot 10^7$ GeV. Fig. 4 depicts energy dependence of the scaled inelasticity $\alpha\langle K \rangle$ (with scaling factor $\alpha \simeq 3.3$) along with experimental data on the average logarithm of the effective nuclear mass number.

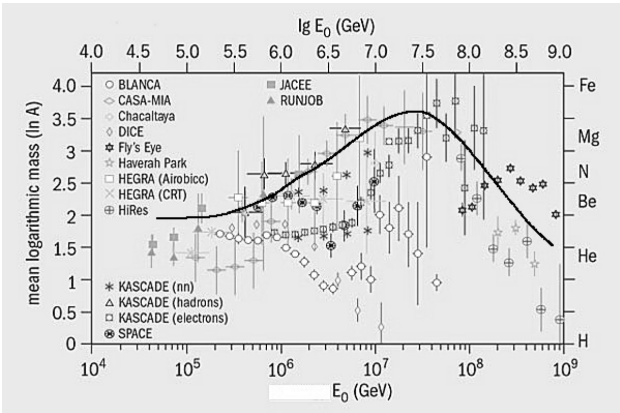

Fig. 4. Energy dependence of the scaled inelasticity and experimental data on the average logarithm of the effective nuclear mass number.

It is also worth to note that the maximum in inelasticity energy dependence, when the pionization component is maximal, is correlated with the minimum of the relative component of protons in the EAS, the following simple relation can be supposed $\Phi_p/\Phi_{all} \sim 1 - \langle K \rangle$, i.e. the relative proton component in the detected EAS should have a non-monotonic energy dependence.

It should be noted that the behaviour of the ratio σ_{el}/σ_{tot} when it goes to unity at $s \to \infty$ does not imply decreasing energy dependence of σ_{inel}. The inelastic cross–section σ_{inel} increases monotonically and it grows as $\ln s$ at $s \to \infty$. Such a dependence of σ_{inel} is in good agreement with the experimental data and, in particular, with the observed falling slope of the depth of shower maximum distribution [20]. The predicted numerical value of the inelastic cross-section is $\sigma_{inel}(s) \simeq 76\ mb$ at the LHC energy $\sqrt{s} = 14\ TeV$. This value is also in a good agreement with the value for this quantity extracted from the proton-air inelastic cross-section [19]. Finally we would like to note that this approach provides a reasonable description [21] of the energy dependence of mean multiplicity and leads to its power-like growth with a small exponent.

Conclusion

The relation of the knee and other effects observed in the EAS measurements with the modification of particle generation mechanism is under discussion since the time when they were discovered. We propose here one particular realization of this idea — an approach where the corresponding particle generation mechanism in EAS is strongly affected by the unitarity effects and the energy region between the knee and the ankle coincides with the transition region to the scattering mode where antishadowing develops at small and then at moderate values of impact parameter, i.e. the energy spectrum of the primary cosmic particles $F_0(E)$ is modulated by the significant variation of the scattering matrix S in the energy region starting from about $E_1 \simeq 10^6$ GeV and finishing at about $E_2 \simeq 10^9$ GeV and this resulting in the regularities in the observed spectrum $F(E)$ measured in the EAS studies. 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 almost not affected. It seems to be a rather natural explanation of the observed regularities in the EAS measurements and has a close interrelation with the nonmonotonous energy dependence of gap survival probability and inelasticity. This hypothesis is based on the saturation of the unitarity and can be experimentally checked at the LHC [10]. The studies of the proton scattering in the forward region at the LHC will be very helpful for improving the interpretation of the results of the cosmic rays experiments.

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