

New approach to cosmic ray investigations above the knee

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Abstract. It is assumed that at energies around the knee the nucleus-nucleus interaction is drastically changed due to production of blobs of quark-gluon matter with very large orbital momentum. This approach allows explain all so-called unusual events observed in cosmic rays and gives a new connection between results of EAS investigations and energy spectrum and mass composition of primary cosmic rays. To check this approach, the experiments in cosmic rays and at LHC are proposed.

1. Introduction

In cosmic ray investigations, the energy region about 10^{15} eV is very interesting and important. Firstly, this region separates two main methods of cosmic ray investigations: direct measurements at satellites and balloons and EAS investigations. Secondly, namely above this energy the basic characteristics of cosmic rays: energy spectrum and mass composition are changed. At the energy about 3 PeV in the spectrum the knee appears and the mass composition becomes heavier. Now all these changes of the energy spectrum and mass composition are explained by cosmophysical reasons, in spite of fact that all experimental results are obtained from EAS observations, and their recalculations to primary cosmic ray parameters are model dependent.

2. Why a new approach is required?

The knee was firstly observed almost 60 years ago [1]. But no exhaustive and consistent description of the knee appearance for this long period was proposed. On the other hand, for this period many unusual results in cosmic ray experiments at energies above the knee were obtained. Among them: Halos, Alignment, Penetrating cascades, Centauros and others [2], which cannot be explained in the frame of existing theoretical models and approaches. Additionally in the last years so-called “muon puzzle” appeared: excess of muons in EAS investigations compared to calculations [3-6] and excess of VHE muons (> 100 TeV) [7].

It is necessary to remark that all these results were obtained at the Earth’s surface at various altitudes after multiple interactions of primary and secondary particles with nuclei of nitrogen or oxygen in the atmosphere. Therefore the results of observations and measurements are strongly dependent on models of such interactions.

Today there is no model which could describe all observed unusual phenomena from a single point of view. All existing models of strong interactions are based on extrapolation of accelerator results to higher energies. However good accelerator data were obtained for pp -interactions only. In cosmic rays most part of interactions are nucleus-nucleus ($\sim 60\%$) and proton-nucleus ($\sim 40\%$). But in the nucleus-



nucleus interactions, even in LHC experiments, serious deviations from existing models are observed. For example, in [8] a more fast increase of secondary particle multiplicity was observed. Of course existing models are being improved and new models appear. But they do not include any serious deviations from existing conception that nucleus-nucleus interaction is a certain sum of nucleon-nucleon interactions.

What is necessary to explain all unusual data obtained in cosmic ray experiments including changes in energy spectrum and mass composition? For that a model of strong interactions is required which must give: threshold behavior, since all unusual events and phenomena appear at energies of several PeV only; large cross-section, which is necessary to observe various unusual events and phenomena in cosmic rays experiments; large orbital momentum to explain the alignment; large yield of VHE leptons to explain excess of VHE muons and penetrating cascades; the change of EAS development and, as a consequence, change of N_μ/N_e ratio and X_{\max} behavior with increasing of energy [9].

Of course these requirements are very unusual and contradictory. For example, since muons cannot be produced in hadron interactions directly, it is necessary to suppose that at the knee energy (about 3 TeV in the center of mass system) some new state of matter with effective mass \sim TeV appears and then decays into leptons. But production of some particle with mass \sim TeV has a very small geometrical cross section $\pi\lambda^2 \sim \pi/m^2 \sim 10^{-34} \text{ cm}^2$ and cannot be observed in cosmic rays. Therefore a new approach to nucleus-nucleus interaction description is required. The most attractive model is that of quark-gluon plasma, though it is better to speak about quark-gluon matter (QGM) since usual plasma is like a gas, and quark-gluon plasma behaves like a liquid.

3. New model of nucleus-nucleus interaction

The main idea of a new model of nucleus-nucleus interactions is the production of some blob of quark-gluon matter, which includes considerable parts of interacting nuclei. This provides the fulfilment of two main requirements to new model of interaction:

- threshold behavior, since for that high temperature (energy) is required;
- large cross-section, since the transition from quark-quark interaction to some collective interactions of many quarks (and gluons) occurs:

$$\sigma = \pi\lambda^2 \rightarrow \sigma = \pi R^2, \quad (1)$$

where R is a size of quark-gluon blob.

For explanation of other observed phenomena a large value of angular momentum is required. As was shown in paper [10], in non-central ion-ion collisions an orbital angular momentum appears. Its value can be very large and is increased with central-of-mass energy \sqrt{s} . As calculations showed [11] the value of this momentum can reach about $\sim 10^4$ in interaction of Au-Au nuclei. Such large orbital momentum changes the situation with decays of QGM blob drastically.

Globally polarized QGM blob with large orbital momentum can be considered as a usual resonance with a large centrifugal barrier:

$$V(L) = L^2/2mR^2, \quad (2)$$

which will be large for light quarks but much less for top-quarks. And though in interacting nuclei top-quarks are absent strong suppression of decays into light quarks gives time for production of heavy quarks in the boiling quark-gluon matter. For top-quarks the centrifugal barrier will be low and decays into $t\bar{t}$ -quarks are possible. This circumstance changes results of nucleus-nucleus interaction in following ways.

1. Simultaneous interactions of many quarks change the value of energy in the center-of-mass system:

$$\sqrt{s} = \sqrt{2m_p E_1} \rightarrow \sqrt{2m_c E_1}, \quad (3)$$

where $m_c = nm_N$, and n – is the number of nucleons in QGM blob. In the first approximation, the minimal value of n can be evaluated as 4 (m_c is the mass of α -particle). But really it can be larger.

This point is important for new model, since it determines the conditions of transition from quark-quark interactions to interaction of many quarks.

2. Produced $t\bar{t}$ -quarks pair takes away from QGM blob at least about 350 GeV ($2m_t$), and taking into account fly-out energy this value can be equal about 700 GeV in the center-of-mass system.

After this drastic decreasing of \sqrt{s} and L correspondingly QGM blob can decay into more light quarks, eventually into u - and d -quarks.

Top-quark has a very short life time (10^{-25} s) and decays into W -boson and b -quark $t(\bar{t}) \rightarrow W^+(W^-) + b(\bar{b})$, b -quark gives a jet, in which transitions $b \rightarrow s \rightarrow u$ are possible. W -bosons decay into leptons ($\sim 30\%$) and hadrons ($\sim 70\%$), mainly pions (in average ~ 20).

These new processes change the development of EAS in the atmosphere. Therefore evaluation of primary particle energy by using measured parameters of EAS without taking into account new processes may give results which are very far from reality.

4. Consequences for CR and LHC

The proposed model can explain all events and phenomena observed in cosmic rays from a single point of view.

Firstly, production of top-quarks and correspondingly W -bosons with a large cross-section gives a possibility to solve “muon puzzle”. Decays of W -bosons into muons and neutrinos explain the excess of VHE muons with energy above 100 TeV and appearance of penetrating cascades [12]. Decays of W -bosons into hadrons (mainly pions, in average ~ 20) explain the increasing number of muon bundles with the increase of energy.

Secondly, all unusual events, observed in cosmic ray experiments above 10^{15} eV: alignment, halos, Centauros, penetrating cascades etc. [13].

Thirdly, it can explain changes of the EAS energy spectrum behavior. Now the transition from the measured EAS parameters to its energy does not take into account a change of EAS development due to a change of the interaction model. To illustrate this circumstance in figure 1 the cascades in the atmosphere initiated by proton and iron nucleus in frame of existing models and initiated by protons in frame of new model. One can see that introduction of t -quark production gives practically the same results as a change of the primary particle. How is the energy spectrum changed in this situation? As a result of EAS development change and taking into account a missing energy taken away by neutrinos and VHE muons, the measured EAS energy E_2 will not be equal to primary particle energy E_1 , and correspondingly the measured spectrum will differ from the primary spectrum. Transition from energy E_1 to energy E_2 gives a bump in the energy spectrum near the threshold of the new state of matter production (figure 2).

How the measured composition is changed in frame of the new model? Since for QGM production not only high temperature (energy) but also high density is required, threshold energy for production of the new state of matter for heavy nuclei will be less than for light nuclei and protons. Therefore heavy nuclei (e.g. iron) spectrum is changed earlier than light nuclei and proton spectra! And measured spectra for different nuclei will not correspond to the primary composition (figure 3). But the energy spectrum of all nuclei will be in a good agreement with experimental data (figure 4).

How to check the new model? In cosmic ray experiments, there are two possibilities [14]. The first one is the measurement of the energy deposit of muon bundles. Changes in this value in dependence on primary particle energy will evident that some new processes of muon generation are included. These measurements can be performed in the NEVOD-DECOR experiment in which the number of muons and their energy deposit can be measured by different detectors [15]. The second one is the measurement of inclusive muon energy spectrum above 100 TeV. Detection of excess of VHE muons will evident for muon generation in decays of heavy particles (e.g., W -bosons). Such measurements can be performed in IceCube.

Good possibilities to check the new model are available in LHC experiments, since such predictions as excess of t -quarks, excess of W -bosons, sharp increase of missing energy, etc. can be

measured by existing LHC detectors. But it is better to do these measurements in AA -interactions (as in cosmic rays) than in pp -interactions. Of course, the search of t -quarks and W -bosons in AA -interactions is a more complex task compared to pp -interactions, due to a very large multiplicity of secondary particles. Apparently, some observations of the effects predicted by the new model were obtained in AA -interactions [16].

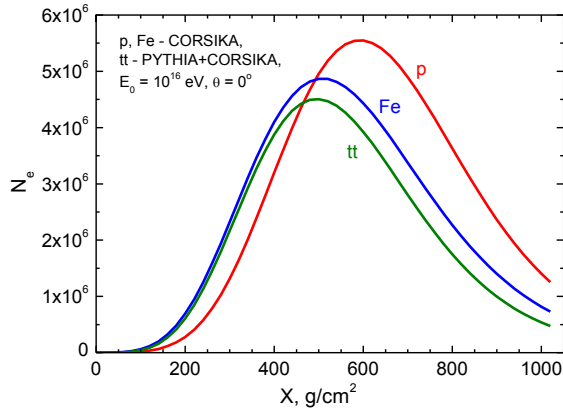


Figure 1. EAS cascade curves in the atmosphere for p, Fe primary particles in the frame of standard interaction model and for protons with production of t -quarks.

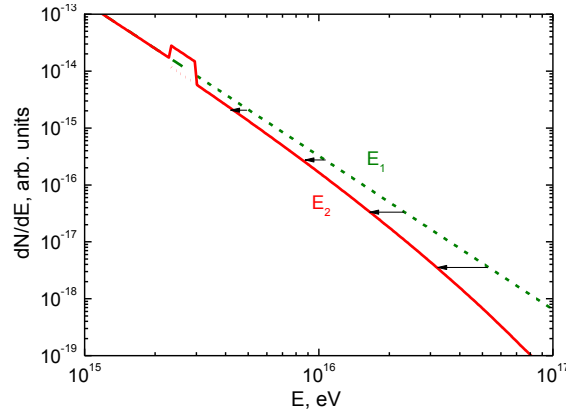


Figure 2. Formation of the measured cosmic ray energy spectrum in frame of the nuclear-physical approach (production of the knee with some “bump”).

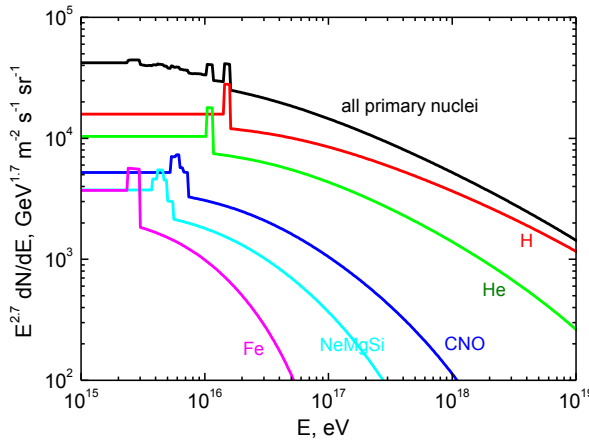


Figure 3. Changes of various CR nuclei spectra in the frame of the considered interaction model.

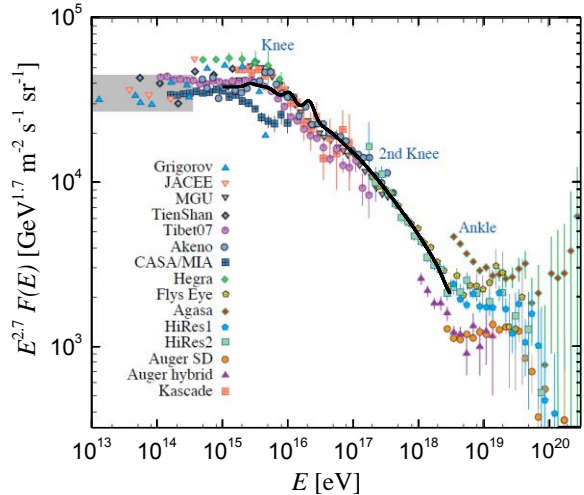


Figure 4. Spectrum calculated in the frame of the new interaction model and experimental data.

5. Conclusion

The considered approach to interpretation of results of EAS measurements allows to solve problems of primary cosmic ray energy spectrum and composition explanation.

Possibilities of searching of a new state of matter with mass \sim TeV exist as in LHC experiments: searches of excess of t -quarks and W -bosons, so in CR experiments – study of the energy deposit of muon bundles (NEVOD-DECOR) and measurements of muon energy spectrum above 100 TeV in IceCube.

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