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Are the primary cosmic ray and EAS spectra the same or not?

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Abstract. Usually it is believed that the energy of extensive air showers (EAS) is equal or is proportional to the energy of primary particle. Of course, taking into account fluctuations in hadron interactions and in the EAS development, some difference between the energies of the EAS and PCR appears but the slopes of the spectra must be the same with a good accuracy. In this talk, an alternative approach, in which the model of PCR interaction at the knee energy is drastically changed, is considered. The consequences for interpretation of results on primary energy spectrum and composition in frame of this model are analyzed. The results agree with experimental data. Some possible experiments to check the predictions of this approach are discussed.

1. Introduction
The main characteristics of primary cosmic rays (PCR) are energy spectrum and composition. The only method of their investigation above $10^{15}$ eV is the study of EAS in the atmosphere and/or at the Earth's surface, and all so-called "experimental data" about energy spectrum and composition of PCR are results of interpretation of EAS parameter measurements.

In principle, two approaches to interpretation of results of EAS parameter measurements are possible. In cosmophysical approach, it is supposed that all serious changes in EAS parameters with increasing of energy are results of PCR energy spectrum and composition change. In nuclear-physical approach, corresponding changes can be connected with interaction model change. But for that really "new physics" must be included into hadron interaction model. Such approach is developed by the author since 1999 [1] and its subsequent development is described elsewhere [2, 3].

2. Cosmophysical approach
The most part of cosmic ray community supports the cosmophysical approach, and all observed changes in EAS parameter behavior are considered from this point of view. The following assumptions are taken into account:

- Energy of primary particles is equal to EAS energy which is evaluated from measured parameters in the frame of one of the known interaction models.
- All changes of EAS characteristics in dependence on energy are results of PCR energy spectrum and composition changes only.
- PCR have galactic origin with limiting energies of their acceleration and keeping in Galaxy, which are determined by particle charge $Z$. 
Results of interpretation of various EAS measurements and their explanation in frame of the cosmophysical approach are given in figure 1, in which the main peculiarities of the energy spectrum are shown: the knee, the second knee, the ankle and GZK-cutoff.

![Figure 1. All-particle energy spectrum of primary cosmic rays and its explanation in frame of cosmophysical approach [4].](image)

As it is seen from figure 1, the both knees are connected with change of PCR composition. But it follows from this figure that the composition must change in favor of heavy nuclei in the beginning slowly, than more quickly up to iron nuclei. But the results of average logarithm of mass number $<\ln A>$ evaluations based of $N_\mu/N_e$ – ratio measurements show another picture (figure 2).

![Fig. 2. Mean logarithmic mass of cosmic rays derived from the average depth of the shower maximum (left), from the measurements of electrons, muons, and hadrons at ground level (right) [5].](image)

Above the knee $<\ln A>$ in the beginning is increased relatively sharply and then more slowly is decreased, and does not reach value $<\ln A> = 4.2$ corresponding to pure iron composition. The same situation is in $X_{\text{max}}$ measurements (figure 3).

Figure 3 also illustrates the fast change of composition to heavy nuclei, then slowly moving back to proton composition. These results do not agree with picture in figure 1 either.
Figure 3. Average depth of the shower maximum $X_{\text{max}}$ as a function of primary energy [5].

3. Nuclear-physical approach

A necessity of this approach consideration is connected not only with mentioned drawbacks of cosmophysical approach, but with other results obtained in investigations of cosmic rays with energies more than $10^{15}$ eV. In many experiments some unusual results were obtained. These results were discussed in various papers (see for example [6, 7]), therefore here the list of these events is presented only.

- In hadron experiments: halos, unusual families, alignment, penetrating cascades, long-flying component, large transferred momenta, Centauros and Anti-Centauros.
- In muon experiments: excess of VHE muons (> 100 TeV) and excess of muon bundles at large zenith angles – so-called "muon puzzle" [8].
- In EAS measurements: the mentioned above change of EAS energy spectrum (the knee), changes in the behavior of $N_{\mu}/N_e$ -ratio and $X_{\text{max}}$ and also excess of young and old showers – all these phenomena must be considered in frame of possible changes of interaction model as unusual.

For explanation of a whole set of unusual events and phenomena, a new model of hadron interaction must satisfy the following requirements:

1. Threshold behavior (unusual events appear at several PeV only).
2. Large cross-section (to be observed in cosmic ray experiments).
3. Large yield of leptons ("muon puzzle", missing energy, penetrating cascades).
4. Large orbital momentum (alignment).
5. Change of EAS development (appearance of missing energy to explain the knee, increasing of $N_{\mu}/N_e$ – ratio, decreasing of $X_{\text{max}}$ production of young and old showers).

Among possible variants of new interaction model (new type of interaction, new massive particle etc.) the most realistic is production of blobs of quark-gluon plasma. Of course, it is better to speak about quark-gluon matter (QGM), which can be considered in frame of known physical laws and rules.

4. Blobs of quark- gluon matter in cosmic rays

Production of QGM blobs provides fulfillment of two main conditions: threshold behavior, since for that a certain temperature (energy) is required; large cross section since in this case the transition from quark-quark interaction to some collective interaction of many quarks and gluons occurs, and geometrical cross section will be changed from $\sigma = \pi \lambda^2$ to $\sigma = \pi R^2$, where $R$ is a size of interacting quark-gluon matter blob.

For fulfillment of other conditions and explanation of corresponding unusual events, a large value of orbital angular momentum is required. The solution of this problem was proposed by two Chinese
physicists [9]. They showed that orbital angular momentum $L$ in non-central ion-ion collisions is produced (figure 4), and its value is increasing with collision energy in the center-of-mass system as $L \sim \sqrt{s}$.

**Figure 4.** Production of orbital angular momentum in non-central ion-ion collisions in the center-of-mass system [9].

Further investigation of such collisions showed that the value of the orbital momentum can be very large. In figure 5, the results of $L$ calculations for Au-Au collisions at the RHIC energy as a function of the impact parameter $b$ in units of the nucleus radius $R_A$ are shown [10].

**Figure 5.** Total orbital angular momentum of the overlapping system in Au+Au collisions at the RHIC energy as a function of the impact parameter $b$ [10].

The appearance of a large orbital momentum leads to production of a centrifugal barrier, which correspondingly will be also increased with grows of $\sqrt{s}$. In the center-of-mass system, the value of the centrifugal barrier for a particle with mass $m$ will be

$$V(L) = \frac{L^2}{2mR^2}.$$  

This barrier will be large for light particles ($u, d, s, c, b$-quarks) but small for heavy particles ($t$-quarks). And though top-quarks are absent in usual hadron matter, the suppression of decay into light quarks gives time for production of even such heavy quarks as top.

Production of $t$-quarks with a relatively large probability drastically changes the hadron interaction model and allows explain many unusual results observed in cosmic rays. Live time of top-quarks is of the order $\sim 10^{-25}$ s and their decay modes are

$$t(\bar{T}) \rightarrow W^+ (W^- + b(\bar{b}))$$

with a consecutive chain of decays $b(\bar{b} \rightarrow c(\bar{c} \rightarrow s(\bar{s} \rightarrow )u(\bar{u}))$. Of course $b$-quark can interact and produce a jet. $W$ – bosons decay into leptons ($\approx 30\%$) and hadrons ($\approx 70\%$). Lepton decay mode
allows explain missing energy and excess of VHE muons. $W$ can decay into $e\nu_e, \mu\nu_\mu, \tau\nu_\tau$, with energy of each lepton about 40 GeV in the center-of-mass system. But taking into account the very large primary particle energy their energy in laboratory system will be more than 100 TeV and will be increased with growth of primary energy. This process gives an excess of VHE muons. Since energy of neutrino is not measured they give missing energy. Hadron mode (mainly pions, on average ~ 20 particles) provides a change of EAS development (by making it more quick) that allows explain changes in the behavior of $N_\mu/N_e$ – ratio and $X_{\text{max}}$.

5. EAS energy spectrum in new approach
In frame of the considered model, the following changes in description of interaction of cosmic rays with nuclei of the atmosphere must appear:

1. Transition from quark-quark interaction to collective interaction of many quarks and gluons must change the formula for energy in the center-of-mass system

$$\sqrt{s} = \sqrt{2m_N E_1}$$

to

$$\sqrt{s} = \sqrt{2m_c E_1},$$

where $m_N$ is the mass of nucleon ($p, n$), $m_c$ is the total mass of many quarks of the target (a part of nuclei of nitrogen or oxygen). In the simplest case, it is possible to believe, that

$$m_c = nm_N,$$

where $n$ can be in the interval $1 \div A$. Such leap in value of $\sqrt{s}$ explains sharp inclusion of new process since the angular orbital momentum $L \sim \sqrt{s}$ and centrifugal barrier $V(L) \sim s$ will be also sharply changed.

2. Production of $t\bar{t}$-pair must decrease $\sqrt{s}$ at least by value $2m_t$ and in a general case by some value $\varepsilon_t$, which will depend on primary particle energy and its mass. Dependence on primary particle mass $A$ is connected with threshold energy for QGM blob production, which depends on $A$ (see formulas below on page 7). Only the remaining part of energy in the center of mass system $\sqrt{s} - \varepsilon_t$ will be converted into the energy of usual processes of EAS development. And standard measurements and evaluation of EAS energy will give the value $E_2 = \left(\sqrt{2m_c E_1} - \varepsilon_t\right)^2 / 2m_c$ which is less than primary particle energy $E_1$. As a result, we will obtain steepening of the measured spectrum though real spectrum does not change its slope.

Figure 6. Formation of measured cosmic ray energy spectrum in frame of nuclear-physical approach.

Figure 6 (left) illustrates a transition from the primary spectrum with a single slope to the measured energy spectrum with a variable slope. If not to take into account this underestimation of energy, the energy spectrum with a bump can be obtained (figure 6, right). Taking into consideration the measured energy straggling, the knee will be imitated.
3. Since for the production of quark-gluon matter not only high temperature (energy) but also high density is required, it is reasonable to assume that firstly QGM will be produced in nucleus – nucleus interactions but not in proton – nucleus interactions. This means that in cosmic ray interactions the first component (at the same energy per nucleus) which will interact with the production of QGM will be iron nuclei (or more heavy), then more light nuclei and the last – protons. Figure 7 illustrates the situation.

![Figure 7](image)

**Figure 7.** Changes of various nuclei spectra in the frame of the considered model.

As a result, the picture of the measured energy spectrum and composition above the knee is drastically changed (figure 8).

![Figure 8](image)

**Figure 8.** Measured changes of contributions of various cosmic ray components to primary spectrum.

Figure 8 is made by an analogy with figure 1. The curves are not results of calculations. They illustrate the principal change of the approach. In figure 1, the changes of primary spectra of different cosmic ray components are shown. In figure 8, the results of measurements of different cosmic ray components are indicated, which really do not change their slopes. So, in this approach the knee is the result of our interpretation of data measurements.

For calculation of all-particle energy spectrum, the simplest model of QGM blobs was used:

\[
e_{j} = 4m_{j} \frac{E_{j}}{E_{th}} \ln \left( 1.72 + \frac{E_{j}}{E_{th}} \right).
\]
Threshold energy $E_{th}$ of QGM blob production is determined by the mass number of primary particle $A$ and was taken into account as

$$E_{th} = E_{knee} \left( \frac{56}{A} \right)^{0.5}.$$ 

Dependence of the compound mass on the mass number of primary particle was taken in the form

$$m_c = 2m_N A^{0.25}.$$ 

Primary spectra of various nuclei were taken as extrapolation from [11]. The 15% straggling of measured energies was assumed. The results of calculations and comparison with experimental data on the all-particle energy spectrum are given in figure 9. Very good agreement is observed.

![Figure 9. Calculated and experimental data on all-particle spectrum.](image)

6. **How to check new approach?**

There are several possibilities to check the new approach as in LHC experiments so in cosmic ray investigations.

Of course, the most convincing results can be obtained in LHC experiments, since the considered approach has a precise signature: sharp increasing of top-quark production. Other predicted peculiarities: the increase of missing energy, excess of muons from decays of $W$-bosons and $b$, $c$-quarks can be observed in LHC experiments, too.

However these results cannot be obtained in $p$-$p$-interactions even at full LHC energy 14 TeV, which corresponds to $10^{17}$ eV in cosmic ray experiments (for $p$-$p$-interaction). If the considered approach is correct then for production of quark-gluon matter with described features at these energies the collisions of sufficiently heavy nuclei are required. But the experiments for searching of $t$-quark in nucleus-nucleus interactions at LHC are not even planned yet. However, the evidences in favour of the considered approach have been obtained in Pb+Pb collisions at LHC: more sharp increasing of secondary particle multiplicity and detection of imbalance events. The analysis of these events in the frame of the considered model was done in paper [12].

In cosmic rays, there are two possibilities to check the considered approach. The first of them are direct measurements in space of primary energy spectra for different nuclei to see if their energy spectra change. But such experiments are not possible in the nearest future since for that very large detectors are required.

The second and more realistic possibility are measurements of characteristics of muon flux in the atmosphere: inclusive muon energy spectrum above 100 TeV and energy deposit of EAS muon component below and above the knee.
Since for VHE (above 100 TeV) muon production the decays of heavy or/and short-lived particles are required, so the indisputable proof of existence of the excess of such muons will uniquely evidence in favor of the realization of the considered scenario. The existence of VHE muon excess in two experiments (Baksan underground scintillation telescope [13] and IceCube [14]) was observed but poor statistics [13] and some methodical uncertainties [14] require further investigations which can be done in IceCube experiment.

Energy spectrum of muon bundles is the only unexplored parameter of EAS and its direct measurements are practically impossible. But evaluation of the energy deposit of muon bundles at various EAS energies and comparison of results of the measurements below and above the knee can give an evidence for interaction model change at energies above the knee. Such experiment is now in progress at the experimental complex NEVOD-DECOR and the first preliminary results do not exclude such possibility [15].

7. Conclusion
Considered approach to interpretation of results of EAS parameters measurements allows solving problems connected with PCR energy spectrum and composition. And apparently for the first time for many ten years the experiments in cosmic rays have serious advantages compared to accelerator ones in searching of a new state of matter.

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