Possible explanation of results of CR investigations in the energy interval $10^{15} - 10^{17}$ eV: Nuclear-physical approach

A A Petrukhin and A G Bogdanov
National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409, Russia

E-mail: AAPetrukhin@mephi.ru

Abstract. Among three possible approaches to explanation of the behaviour of CR energy spectrum and mass composition in the energy interval $10^{15} - 10^{17}$ eV: methodical, cosmophysical and nuclear-physical, the last of them is considered. A possibility of a new massive state of matter generation in interactions of CR with such energies is discussed. As a possible version, the production of blobs of quark-gluon plasma with a large orbital momentum is considered.

1. Introduction
Energy region $\sim 10^{15} - 10^{17}$ eV is very interesting and important. Firstly, in this region direct measurements at satellites are impossible and only EAS investigations can be performed. Secondly, namely in this region basic characteristics of cosmic rays (CR): energy spectrum (the knee, the 2nd knee) and mass composition (becomes more heavy) are changed. But the second statement is incorrect since there are no direct experiments in which the energy spectrum and mass composition above $10^{15}$ eV are measured. Really we can measure EAS parameters only. The scheme of cosmic ray investigations by means of EAS observables is given in figure 1.

![Diagram](image)

Figure 1. Existing approach to EAS data analysis [1].
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What is the situation now? Today it is believed that the model of hadronic interactions is not changed significantly with increasing of energy at least up to $10^{17}$ eV. The reason is simple. No serious deviations from SM in pp-interactions up to energy 13 TeV (~ $10^{17}$ eV in laboratory system) in LHC experiments were observed. But cosmic rays consist mainly of nuclei (table 1) which interact with atomic nuclei of nitrogen or oxygen. Total amount of nuclei is about 60% at normal composition (without heavierying).

Table 1. Cosmic ray mass composition.

| Particles   | Z | A | Energy per nucleon | Energy per nucleus |
|-------------|---|---|-------------------|-------------------|
| Protons     | 1 | 1 | 92%               | 42%               |
| α-particles | 2 | 4 | 7%                | 21%               |
| Light nuclei| 3-5|10 | 0.25%             | 1%                |
| Medium nuclei| 6-10|15 | 0.5%              | 18%               |
| Heavy nuclei| ≥11|32 | 0.25%             | 18%               |

2. Why a new approach is required?
Now all changes in measured EAS parameters are explained by changes of the energy spectrum and mass composition. And at a first glance there are no reasons to change the interaction model.

But no exhaustive and consistent description of the knee for almost 60 years was proposed. At the same time, many unusual results in cosmic ray experiments at energies above the knee were obtained. In the last years, so-called “muon puzzle” in CR investigations appeared (excess of VHE muons and muon bundles compared with calculations). In nucleus-nucleus interactions even in LHC experiments serious deviations from existing models are observed (see figure 2).

Figure 2. Multiplicities of charged particles produced in nucleus–nucleus and proton–proton collisions as a function of collision energy [2].

3. New model of nucleus-nucleus interaction
What do we need to explain all these data? Model of hadronic interactions which gives:
- threshold behaviour (all changes in CR appear at several PeV only);
- large cross section (to change EAS spectrum slope);
- increasing yield of secondary particles (excess of pions, muons and muon bundles).
Production of blobs of quark-gluon plasma (or better, quark-gluon matter, QGM) is very suitable for that.

Production of QGM provides two main conditions:
- threshold behaviour, since for that high temperature (energy) is required;
- large cross section, since the transition from quark-quark interactions to some collective interaction of many quarks and gluons occurs: \( \sigma \sim \pi R^2 \rightarrow \sigma \sim \pi R^2 \), where \( R \) is a size of quark-gluon blob.

But for explanation of other observed phenomena a large value of orbital angular momentum is required. The question about the orbital momentum which must appear in nucleus-nucleus interactions is usually not considered. A possibility of its appearance in non-central ion-ion collisions was considered in paper [3]. Corresponding scheme is presented in figure 3. Further investigations showed [4] that the value of the orbital momentum can reach \( L \sim 10^4 \).

A blob of globally polarized QGM with large orbital angular momentum can be considered as a usual resonance with a large centrifugal barrier. Centrifugal barrier \( V(L) = L^2 / 2mR^2 \) will be large for light quarks but much less for \( t \)-quarks or other heavy particles. Though in interacting nuclei \( t \)-quarks are absent, the suppression of decays into light quarks gives time for the appearance of heavy quarks.

How interaction is changed in frame of a new model? Simultaneous interactions of many quarks change the energy in the center of mass system drastically: \( \sqrt{s} = \sqrt{2m_N E_1} \rightarrow \sqrt{2m_N E_1} \), where \( m_c \approx nm_N \). At threshold energy, \( n \approx 4 \) (\( \alpha \)-particle). Produced \( t \)-quarks take away energy \( \varepsilon_t > 2m_t \approx 350 \) GeV, and taking into account fly-out energy, \( \varepsilon_t > 4m_t \approx 700 \) GeV in the center of mass system. Top-quarks decay very quickly: \( t(T) \rightarrow W^+(W^-) + b(\bar{b}) \), \( W \)-bosons decay into leptons (\( \sim 30\% \)) and hadrons (\( \sim 70\% \)); \( b \)-quarks produce jets which generate pions decaying into muons and neutrinos.

4. CR energy spectrum and mass composition in the new approach

How the energy spectrum is changed? One part of \( t \)-quark energy gives the missing energy (\( \nu_e, \nu_\mu, \nu_\tau, \mu \)), and another part changes EAS development due to increasing multiplicity of secondary particles. As a result, measured EAS energy \( E_2 \) will not be equal to primary particle energy \( E_1 \), and the measured spectrum will differ from the primary spectrum (figure 4). Transition of particles from energy \( E_1 \) to energy \( E_2 \) gives a bump in the energy spectrum near the threshold.
Figure 4. The change in the CR energy spectrum at the appearance of the missing energy.

How the measured composition is changed in frame of the new approach? Since for QGM production not only high temperature (energy) but also high density is required, threshold energy for production of 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. Measured spectra for different nuclei will not correspond to the primary composition. If to propose that CR composition is not changed with increasing of energy, the composition recalculated from results of EAS measurements begins to change due to increasing probability of heavy nuclei interactions.

5. Conclusion
To explain the behavior of CR energy spectrum and mass composition at energies $10^{15} - 10^{17}$ eV in the frame of nuclear-physical approach, the production of quark-gluon blobs with a large orbital momentum is required.

This approach can be checked as in cosmic ray so in LHC experiments. In cosmic rays some excess of very high energy muons and neutrinos (> 100 TeV) must appear. In LHC experiments some excess of $W$-bosons or/and $t$-quarks and missing energy must be detected.

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