Cosmic rays above the knee: experimental results and their interpretation

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Abstract: In spite of more than 50 year investigations, the problems of the knee origin and cosmic ray energy spectrum and mass composition above it did not find a contented solution. In this paper, two possible interpretations of results of EAS investigations − cosmophysical and nuclear-physical ones − are compared. In frame of the first one, there are serious difficulties with explanation of mass composition changes above the knee. Opposite, recent application of nuclear-physical approach for this purpose gave very impressive results. This approach allows to solve all problems connected with cosmic ray energy spectrum and mass composition investigations and explain the detection of various unusual events in different experiments above the knee, too.

Keywords: primary spectrum, composition, the knee, unusual events

1 Introduction

Very high energy cosmic rays (> 10^{15} eV) give us information about processes of their acceleration, propagation and interaction. But unfortunately direct measurements of two main CR characteristics: energy spectrum and mass composition at such energies are practically impossible. Therefore all information is obtained from results of EAS investigations. At that, measured parameters: N_e – number of charged particles (mainly electrons), N_μ - number of muons, E_h – energy deposition of EAS core, F_C and F_f – fluxes of Cherenkov and fluorescence radiations from cascade shower in the atmosphere, $X_{\max}$ – the depth of maximum shower development, depend on three unknown functions: energy spectrum, mass composition and interaction model (Fig.1). Therefore there are two possibilities of the interpretation of the measured data: cosmophysical (changes of primary cosmic ray energy spectrum or/and mass composition) and nuclear-physical (changes of interaction model). But, in spite of the fact that in the first paper about the observation of the knee in the measured spectrum of N_e these two possibilities of its explanation were discussed [1], in further investigations only cosmophysical possibility was considered. And the following results where obtained: the knee (3 ÷ 5 PeV), a fast transition to a heavy mass composition above the knee, the second knee (~ 10^{17} eV), the ankle (~ 5 × 10^{18} eV), and contradictory results about mass composition around and above the ankle.

2 Cosmophysical approach

In cosmophysical approach, it is supposed that characteristics of interaction model are known (by extrapolation of accelerator data), and energy spectrum and composition can be evaluated as it is shown in Fig. 1. Other assumptions in this approach are the following: EAS energy is equal to the energy of primary particle. All changes of EAS characteristics in dependence on energy are results of energy spectrum or/and composition changes only. Primary cosmic rays around the knee have galactic origin, and their acceleration and keeping in Galaxy are determined by their charge Z or/and mass *A*.

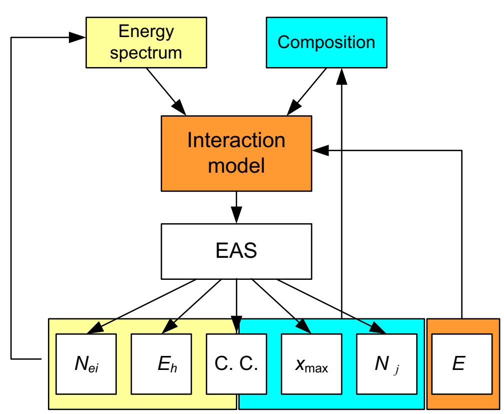

Figure 1. Possible approaches to EAS analysis [2].

The results of interpretation of EAS measurements in frame of cosmophysical approach are well known and discussed in many papers (see f.e. [3 ‒ 5]). At the knee energies, protons begin to reach their acceleration limit or/and leave the Galaxy, and the slope of energy spectrum becomes steeper. Then the slope helium nuclei spectrum increases, etc. In frame of this model the composition must be changed in favor of heavy nuclei, first slowly, then more quickly up to iron nuclei (and may be heavier). But experimental situation is the opposite. In Fig. 2 [3] the results of evaluations of the average logarithm of mass number <ln*A*> based on N_μ/N_e-ratio measurements are shown.

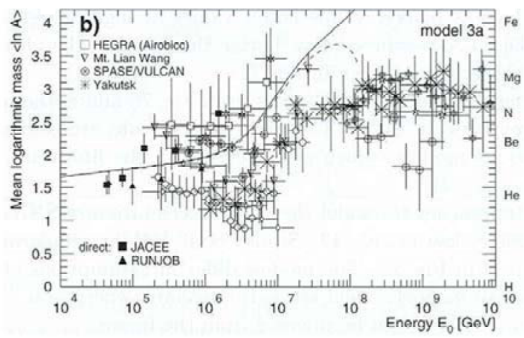

Figure 2. Results of mean logarithmic mass evaluations from N_μ/N_e-ratio measurements [3].

Above the knee, <ln*A*> first increases relatively sharp and then more slowly, and does not reach the value ln*A* = 4, which corresponds to pure iron composition. A similar situation is observed with shower maximum depth $X_{\max}$ measurements. Results (Fig. 3 from [4]) show a fast change of composition after the knee to iron nuclei, then slowly moving back to protons. These contradictions stimulate consideration of nuclear-physical approach to EAS data explanation. At that, there are other evidences in favor of interaction model changes above the knee.

3 Nuclear–physical approach

The main suppositions of this approach are the following. The energy spectrum and mass composition of primary cosmic rays are not changed seriously, and the knee is the result of inclusion of new processes of interaction or/and production of new particles, states of matter, etc. Of course, in this case the evaluated EAS energy is not equal to primary particle energy:

$$E_{\mathrm{EAS}} = E_2 < E_1. \quad (1)$$

For that, fulfillment of at least one of two conditions is required: 1) Missing energy (e.g., neutrino and muon energies which can be taken into account on the basis of calculations only) is sharply increasing. 2) Development of EAS is changed in such a way that EAS energy evaluated on the basis of usual theoretical models becomes underestimated.

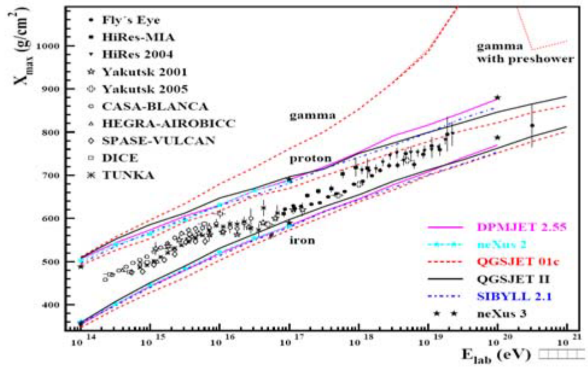

Figure 3. Results of $X_{\max}$ measurements [4].

In favour of possibility of appearance of new processes evident numerous unusual events which were detected in various experiments at energies above the knee. These unusual events were analyzed in many papers (see f.e. [6, 7]). Therefore, let us list these events and phenomena only. In hadron experiments: halos, unusual families, alignment, penetrating cascades, long-flying component, large transverse momenta, Centauros and Anti-Centauros; in muon experiments: excess of muons in their energy spectrum at energies more than several tens TeV, observation of VHE (> 100 TeV) muons in some experiments.

To explain all these unusual events and phenomena from a single point of view, a new model of interaction must satisfy the following requirements: threshold behaviour and large cross section, large orbital momentum and large yield of leptons. As it was shown in paper [8], quark-gluon plasma (QGP) model allows to combine these inconsistent conditions. Of course it is better to use the term quark-gluon matter (QGM), since the usual plasma is similar to a gas, but quark-gluon matter behaves as a liquid.

Production of blobs of QGM provides the fulfillment of two main conditions: the threshold behaviour, since for that a certain temperature (energy) is required, and the 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

$$\text{from } \sigma = \pi\lambda^2 \text{ to } \sigma = \pi(\lambda + R)^2 \text{ or } (R_1 + R_2)^2, \quad (2)$$

where R, R_1, R_2 are sizes of interacting quark-gluon matter blobs.

As it was shown by Zuo-Tang Liang & Xin-Nian Wang [9], in non-central ion-ion collisions a globally polarized QGM with orbital angular momentum L is produced, the value of which is increasing with the increase of collision energy in the center of mass system: $L \sim \sqrt{s}$.

Correspondingly, centrifugal barrier will be also increased with growth of $\sqrt{s}$. In this case, the blob of quark-gluon matter may be considered as a usual resonance state with a large centrifugal barrier, and its value in the center of mass system will be

$$V(L) = L^2/mr^2. \quad (3)$$

This barrier will be high for light particles (*u*, *d*, *s*, *c*, *b*-quarks) but low for heavy particles (*t*-quarks). And though top-quarks are absent in a usual hadron matter, the impossibility of fast decay into light quarks gives some time for production of even such heavy quarks as top.

Production of *t*-quarks with relatively high probability drastically changes the hadron interaction model and allows to explain many unusual results observed in cosmic rays.

4 How are the results of energy spectrum and composition measurements changed?

Simultaneous interactions of many quarks change the energy in the center of mass system drastically:

$$\sqrt{s} = \sqrt{2m_N E_1} \to \sqrt{2m_c E_1}\ , \quad (4)$$

where m_N is nucleon mass, and m_c is compound mass of many interacting quarks of the target (nuclei of nitrogen or oxygen). For calculations, one can consider $m_c = nm_N$ ($n = 1 \div A$).

Production of $t\bar{t}$ -quark pair must decrease $\sqrt{s}$ at least by the value of $2m_t$, and in a general case by some value $\varepsilon_t > 2m_t$ which will depend on primary particle energy and its mass. The residual part of the energy in the center of mass system ($\sqrt{s} - \varepsilon_t$) will be converted into the energy of usual processes of EAS development. Of course, some part of the energy taken away by top-quarks will be re-injected into EAS development, but in the first approximation, to simplify consideration, it is possible to neglect this value. So, results of standard measurements and standard procedure of evaluation of EAS energy will give value E_2

$$E_2 = \frac{\left(\sqrt{2m_c E_1} - \varepsilon_t\right)^2}{2m_c}, \quad (5)$$

which is less than the energy of the primary particle E_1, and we will obtain the steepening of the observed spectrum.

Fig. 4a illustrates the transition from primary spectrum with a constant slope to 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 (Fig. 4b). Taking into consideration the measured energy straggling, the knee will be imitated.

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 at first 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 production of QGM will be iron nuclei (or more heavy ones), then more light nuclei, and only the last ones protons. Fig. 5 illustrates the situation. For calculations, primary spectra of various

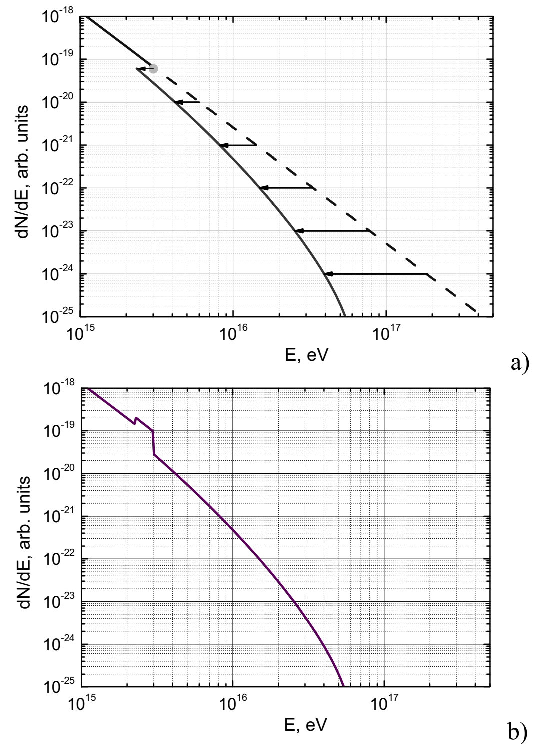

Figure 4. Formation of measured cosmic ray energy spectrum in frame of nuclear-physical approach.

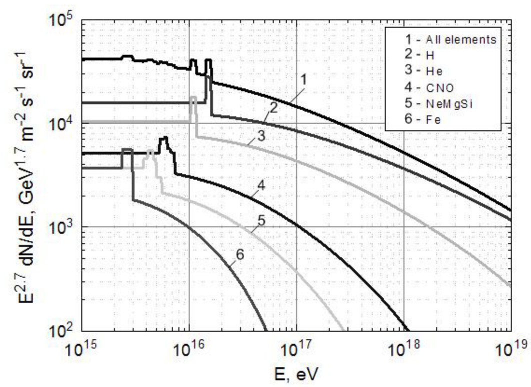

Figure 5. Changes of various nuclei spectra in the frame of the considered model.

nuclei were taken from [10]. The 15% straggling of measured energies was assumed. The results of calculations and comparison with experimental data on all-particle spectrum are given in Fig.6. Very good agreement is observed.

5 Discussion

Energy spectrum obtained in frame of the simplest model surprisingly well describes experimental data. Observed changes of composition are also explained. A sharp increase of average mass above the knee is the result of additional detection of EAS from heavy nuclei. At higher energies, a slow transition to more light nuclei (up to protons) begins. Results of composition changes obtained by means of N_μ measurements are explained, too. Number of muons is increasing as a result of muon production not only in a usual picture of EAS development, but also through decays of heavy particles.

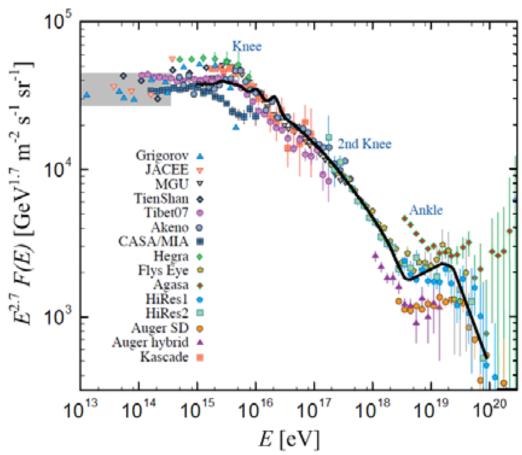

Figure 6. Calculated and experimental data.

In frame of the considered nuclear-physical approach to interpretation of cosmic ray energy spectrum measurements it is easy to explain the ankle appearance. With the increase of the interaction energy the mass and excitation energy of quark-gluon blob will be increased and can become so large that the resonance state will begin to decay into light quarks. Missing energy and other effects connected with production of heavy quarks will be decreased and the development of EAS will return to a normal behavior. Correspondingly, the measured spectrum must return to the primary slope ($\approx$ 2.7) and its behavior at higher energies will depend on the relation between positions of the ankle and the GZK cutoff (Fig.6). More detailed discussion of this problem is given in papers [8, 11].

How to check the new approach? The first possibility is direct measurement of primary energy spectra for different nuclei. In these experiments, missing energy will also appear, and existing power type energy spectra will be changed as shown in Fig. 4. Let us underline once again, that the energy spectra shown in Fig. 4 are not real ones, but are results of interpretation of experimental data without taking into account new processes connected with QGM production.

The second possibility represents the measurements or evaluations of energy characteristics of muon flux in the atmosphere (Fig. 1): inclusive muon energy spectrum above 100 TeV or energy deposit of EAS muon component below and above the knee. The first results of investigation of inclusive muon energy spectrum above 100 TeV were obtained by means of the analysis of Baksan Underground Scintillation Telescope data on the basis of pair meter technique, which gave some excess of such muons, though with poor statistics [12]. The second possibility – comparison of the energy deposit of EAS muon component below and above the knee has not been realized at present, though the change of energy deposit per one muon with increasing of energy can give a good evidence for appearance of very high energy muons. To realize these two possibilities, existing muon and neutrino detectors (BUST, NEVOD-DECOR, IceCube, Baikal, ANTARES, etc.) can be used.

6 Conclusion

Considered nuclear-physical approach allows to solve practically all problems of cosmic ray investigations above the knee. If this approach is correct, it will be an excellent present to 100 year anniversary of cosmic ray discovery!

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