Status, methods and aims of the knee investigations at CR spectrum

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Abstract. Usually it is supposed that the definition of the CR mass composition in knee region is the key to problem of CR spectrum modification in this range. However tens of experiments done for the last half a century, have not decided this problem. The possible causes of fiasco and arguments in favour of necessity to reformulate a method of attack are discussed. It is formulated that the first experimental task now is to solve a more simple problem: is there abnormal CR component in knee field or not. It seems that impossible to formulate correctly more common problem of mass composition without solving of this one. The observational basis is discussed. The hypothesis of strange quark matter is suggested for the abnormal component.

1. Introduction
Two ranges of power CR spectrum represent the special interest: range at >10¹⁹ eV of expectation spectrum end and range 10¹⁵-10¹⁸ eV of a so-called knee. In the field of energies >10¹⁹ eV recent experiments HiRes and Auger [1] were confirmed the data of experiment Agasa about existence of showers with energy ~10²⁰ eV (figure 1). All experiments show bump at 10¹⁵-10²⁰ eV. It is possible only to guess about further spectrum behaviour.

![Figure 1. CR spectrum measured at experiments HiRes and Auger.](image1)

![Figure 2. N_e spectra for EAS and “young” EAS with s<0.4.](image2)

It is possible that spectrum have be proceed with the same spectral index γ≈-3, or be cut off according to GZK-effect predictions. From existing designs only probably satellite design EUSO have large enough geometric factor SΩ for sufficient statistic obtaining at area >10²⁰ eV and resolve this problem. So this reason the problem of knee is a main interest to us.
2. Experiment and the theory

Many models of a knee were made for 50 years of investigations but it is possible select only three basic variants. The first one is connected with reaching of the maximum energy of CR acceleration in sources (an accelerating model), the diffusive model bounds to CR propagation in Galactic and model of a close single source. However there are experimental data which contradict both an accelerating and diffusive model.

Main CR nuclear components must change a spectral indexes at equal magnetic rigidity $R=E/Z=3\cdot10^{15}$ V in these models. As a result CR weight increase behind a spectrum break.

Figure 2 [2] shows the experimental $N_e$-dependence for all EAS and the youngest EAS. Part of “young” EAS with "age" parameter $s<0.4$ is increased from ~10% to 50%, that indicates increase of light nuclei part (p and He) behind a break.

Besides, both these models predict smooth change of a spectrum slope, whereas the sharp spectrum break is observed in experiment.

The problem is removed by means of a close single source model [3] which realizes the certain compromise at the expense of two-component CR composition.

In that case the one part of CR has a smooth spectrum, matching to one of the previous models, and another part has sharp spectrum of a close single source which consists of one (at $E=3\cdot10^{15}$ eV) or two bumps (at $E=3\cdot10^{15}$ and $10^{17}$ eV) as figure 3 demonstrates [2].

Though formally two-component model presents a good approximation of the real spectrum form in knee area there are a number of unresolved problems which call for a more close look.

![Figure 3. CR spectrum measured at experiments HADRON (Tien-Shan) and AGASA.](image1)

Some experimental results, basically received on the Tien-Shan station force to introduce exotic explanations of them, in particular presence of the new CR component such as corpuscles of strange quark matter (SQM) at range of the knee:

(a) First of all a hadron long flying component of EAS was detected by means of a big ionization calorimeter [4]. The hadron absorption length is increased twice from 500 to 1000 g/cm$^2$ in the area of a CR spectrum break (at $E=3\cdot10^{15}$ eV);

(b) The absorption curve of high energy $\gamma$-quanta ($\pi^0$) in an atmosphere is shown in figure 4, which was received by compilation of various emulsion chamber (EC) experiments. This curve may be presented as the sum of two curves where one of them has usual absorption length $\lambda_{abs} \approx 90$ g/cm$^2$ and another (abnormal) has $\lambda_{abs} \approx 250$ g/cm$^2$ [5];

(c) Anomalously narrow EAS with age parameters $s<0.4$ are practically absent in the model calculations, i.e. their presence at experimental events in itself is exotic. Besides just such showers with abnormal narrow lateral distribution functions (LDF) of electrons form the second bump in figure 3 at $E=10^{17}$ eV;

(d) Two bumps in $N_e$ spectrum may be explained as a contribution of two different close sources, however the hypothesis of SQM allows to manage with only one source (quark star). In this case two bumps in $N_e$ spectrum can be derived from one bump at energy spectrum because of big difference of
total number of charged particles in cases when primary strangelet has disintegrated on hundreds hyperons over installation and has attained it without disintegration;

c) EC usage as EAS core detector in hybrid experiment HADRON [6] has allowed receiving $N_e$ dependences for muon and hadron components of EAS with $\gamma$-families. These dependencies contradict each other if primary particles are nuclei. A new CR component such as strangelets has been introduced to eliminate this contradiction.

In figure 5a the $N_e$ dependences of an average muon number for all EAS and EAS with $\gamma$-families are shown. As EAS with $\gamma$-families considered to be proton EAS mainly, their muon number has to be smaller than for all EAS (dotted line), but experiment shows an opposite result. It contradicts any EAS models if primary particles are nuclei.

Besides in figure 5b the $N_e$ dependence of slope $b$ at energy spectrum of $\gamma$-quanta is shown ($E_\gamma^{-b}$). It follows from model calculations, that value $b=2$ matches pure iron and $b=1$ pure protons. Really value of $b$ decreases from $b=1.8$ (mix composition) down to $b=1.2$ (almost purely proton). The increased muon number in these events contradicts any nuclear model of interacting and any nuclear composition. In our opinion the availability of such inconsistency is a sufficient condition for introducing SQM hypothesis.

3. Discussion

The presence capability of an abnormal CR component cardinally changes the approach to planning of ground-based experiments. As a rule solution of a knee problem one’s see in definition of CR nuclear composition and its dependence from a primary energy.

The determination of muon component yields main method of CR composition definition. However, as follows from the previous data, the behaviour of muon component in the knee region essentially differs from the model one.

It is possible to tell the same about behavior of $\gamma$-quanta with energies a few TeV and more. Really it shows behavior of a hadron spectrum since $\gamma$-quanta of such energies derivate from disintegration of $\pi^0$-mesons. Harder hadron spectra behind a break ($N_e \approx 1.5 \cdot 10^6$) contradict CR weight increase in this range.

Escaping of this situation can be bound to the additional component in two-component CR model, assuming that it is responsible for all anomalous effects. Such version basically is possible with assumption, for example, that the close source is quark star and flux of SQM particles goes from it. The locality of such component limiting its presence only by knee region can be explained by metastability of SQM corpuscles. If the time of their life is restricted by an order value $\tau \approx 10^6$ years the investment in CR flow will be yielded only by the most proximate sources, and is possible only one source.

The offered hypothesis is based on experimental results, but is exotic enough and naturally demands verification. EAS check of this kind is possible only on the basis of detailed studying of EAS
core. The unique detector, allowing adequately solving this problem is EC exposed as a part of high-
mountainous EAS installation involving also the muon detector.

In the inference we will show the possible cause of why the problem of CR composition in the
region of knee is not solved till now. In article [7] the elementary model of two-component CR are
used for approximation simultaneously two spectra: EAS spectrum and EAS spectrum with γ-families.
The nuclear spectra are shown in figure 6 at rigidity units.

Figure 6. Nuclear spectra of magnetic rigidity R=E/Z (model), normalized at experimental
data.

As follows from the figure 7 oscillations of a CR composition in that case exceed resolving power
of EAS method. The situation would become more complicated if additional component such as
particles of SQM is introduced.

Figure 7. Total and nuclear spectra of energy (model), normalized at experimental data.

4. The conclusion
The search of the abnormal CR component (or the demonstration of its absence) has to be the main
goal of the new experiments.

Only high mountain complex EAS installation with minimal composition: e- detector, µ-d detector,
EAS core-detector and emulsion chamber can resolve this problem. Undoubtedly, installation addition
with other subsystems only will strengthen it potential.

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