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NEVOD–DECOR experiment and evidences for quark–gluon plasma in cosmic rays

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ABSTRACT

New method of EAS investigations by local muon density spectra and results of muon bundles detection in NEVOD–DECOR experiment are considered. The observed excess of muon bundles from very high energy cosmic rays and results of some other experiments which are evident for an additional flux of very high energy muons are analyzed. A possibility of their explanation through quark–gluon plasma blob production and its consecutive decay is discussed. The ways of experimental checks of this model are considered.

1. Introduction

During 75 years of EAS studies, various methods of their detection were proposed and realized. Several years ago our collaboration proposed and implemented a new method of EAS investigations by local muon density spectra (LMDS) [1]. This method can be used for any EAS directions, but it is especially effective for inclined EAS. Very sharp dependence of atmosphere parameters on zenith angle opens possibility of EAS investigations in a very wide energy range by means of a single and relatively small detector. Namely such detectors are used in the NEVOD–DECOR experiment. The preliminary results of the study were reported at the first RICAP conference [2].

In this paper, results of the NEVOD–DECOR experiment based on the full statistics which were firstly reported at 15th ISVHECRI [3] are considered. The observed excess of muon bundles at high cosmic ray energies and results of other experiments which are also evident for the appearance of an additional muon flux are discussed.

2. New method of EAS investigations

From the point of view of the relation between EAS energies and detector sizes, all known methods can be divided into two groups. Traditional methods of various EAS component detection (number of charged particles, number of muons, energy deposit of EAS cores, and air Cherenkov radiation) require the increase of the array size with the growth of studied EAS energies (e.g., among the recent experiments, KASCADE-Grande and Tunka). For other methods of EAS detection (fluorescence light and radio emission) the sizes of the arrays only weakly depend on EAS energies, and their statistical possibilities are determined by the effective area from which the showers can be collected.

Method of local muon density spectra (LMDS) belongs to the second group. Its possibilities depend on EAS transverse sizes in muon component. Therefore it is very effective for inclined EAS, transverse sizes of which are increasing very rapidly with the increase of zenith angle (see Fig. 1) due to the increase of the distance between points of EAS observation and muon generation (15–20 km for vertical direction and up to 500–600 km for near horizontal direction). Due to the same reason, a fixed density of EAS muons at different zenith angles corresponds to substantially different energies of primary particles. This dependence is additionally enhanced due to muon deflection by the Earth's magnetic field (EMF).

It is important to mark that in this method the sizes of the muon detector determine the lower limit of accessible EAS energies: approximately 10^{15} eV for $S \sim 100$ m^2, since the minimal number of registered muons in a bundle must be not less than 3. Maximal measurable multiplicity of muons in bundles depends on the sizes of detector cells in which each muon must be detected separately. So the total dynamic interval of investigated EAS energies will be determined by the product of two dynamic ranges, those of multiplicity and of zenith angles.

3. Results of the NEVOD–DECOR experiment

Experimental complex NEVOD–DECOR includes two main detectors: Cherenkov water detector NEVOD with volume

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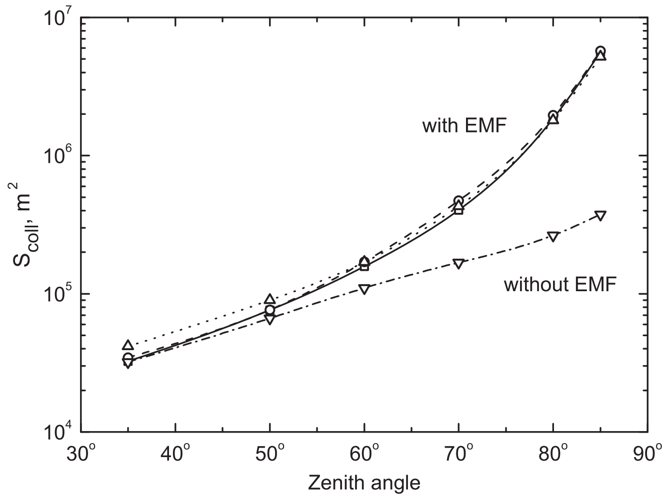

Fig. 1. Effective area of EAS collection in LMDS technique. Different line styles correspond to calculations for different primaries and interaction models. The lower curve: calculation with "switched-off" geomagnetic field.

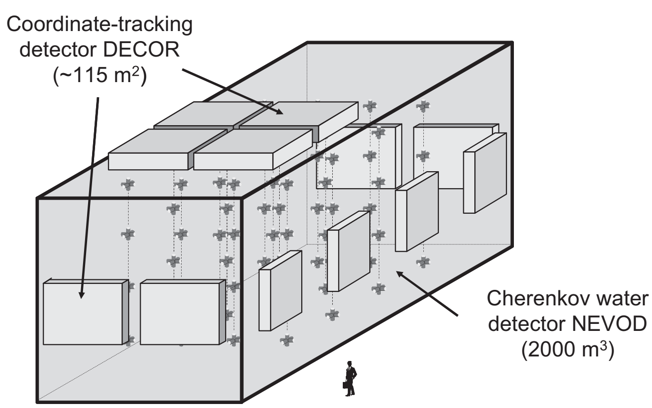

Fig. 2. Experimental complex NEVOD–DECOR.

2000 m^3 and coordinate-tracking detector DECOR with total area 115 m^2, which consists of two parts (Fig. 2): the side DECOR (70 m^2) and the top DECOR (45 m^2).

The side DECOR has a vertical orientation of streamer tube chamber planes in order to detect inclined EAS at large zenith angles. Spatial and angular accuracies of muon track location are about 1 cm and better than 1°, respectively. In Fig. 3, two examples of near horizontal muon bundles are presented; X-projection corresponds to zenith angle θ measurements, Y-projection—azimuth angle φ.

During 5 years (2002–2007), more than two million muon bundles in the zenith angle interval 30°–85° were detected (the total live time about 20 000 h). For the physical analysis, at large zenith angles and high muon multiplicities the whole statistics was used, while for smaller zenith angles and multiplicities only the part of accumulated data (Table 1, Ref. [3]).

Correspondence between local muon density, zenith angles and EAS energies, as foreseen by Monte Carlo simulations, is shown in Fig. 4; the polygons outline the regions corresponding to different muon multiplicities and zenith angles. It is seen from the figure that experimental data cover about four orders of magnitude in EAS energies.

The obtained experimental data were compared with results of MC simulations based on the CORSIKA code (Fig. 5). At simulations, a usual energy spectrum of primary cosmic rays was assumed (with integral slope $\gamma = 1.7$ for $E_0 \leq E_{\rm knee}$, $E_{\rm knee} = 4$ PeV, and $\gamma = 2.1$ for $E_0 > E_{\rm knee}$). As for primary particle composition, two limiting hypotheses were considered: pure hydrogen and pure iron. Also two well-known models of interactions of high energy particles were applied.

From Fig. 5, it is clearly seen that there is a good agreement between calculations and experimental data in the interval 10^{15}–10^{16} eV at normal composition of primary particles. But the further increase of primary energy leads to the increase of experimental LMDS compared to calculations. This circumstance can be interpreted as the composition becomes heavier (up to pure iron). However, at highest energies experimental data indicate the composition even heavier than iron. Progressive deficit of muons in simulated EAS may indicate the presence of new processes for the muon generation.

4. New physics in cosmic rays

Description of very high energy cosmic ray interactions is based on extrapolation of existing models from accelerator energies up to maximal energies of cosmic rays (about 10^{20} eV), and no new physical hypotheses are included in these models. However, many experimental data and unusual events observed in cosmic rays seem to indicate the occurring of new physics at energies in the interval 10^{15}–10^{16} eV.

These unusual events are discussed in many papers (see, e.g., Refs. [4,5]), therefore let us list them here:

- in hadron experiments: halos, alignment, penetrating cascades, long-flying component, large transverse momenta, Centauros, Anti-Centauros;
- in muon experiments: excess of VHE (~ 100 TeV) single and multiple muons;
- in EAS investigations: changes of $N_\mu(N_e)$ and $X_{\max}(N_e)$ dependences.

For explanation of these phenomena and unusual events many theoretical ideas and models were proposed, however they all describe, in the best case, several unusual results but not all of them. To describe all observed unusual phenomena, a new model of hadron interaction is necessary, which has to satisfy the following requirements:

- threshold behavior (unusual events appear at several PeV only);
- large cross-section (to be detectable in cosmic ray experiments);
- large yield of leptons (to explain the observed excess of muons in various experiments and to provide possibility of explanation of some other observed phenomena);
- large orbital (or rotational) momentum (to explain the alignment);
- faster development of EAS (for increasing N_μ/N_e ratio and decreasing $X_{\max}$ elongation rate).

Among various ideas and models which were proposed for this goal (inclusion of a new, e.g., super-strong interaction, appearance of new massive particles, e.g., super-symmetric, Higgs bosons, long-lived resonances, etc.), the most realistic is the production of blobs of quark–gluon plasma (QGP). The discussion about the terms (quark–gluon plasma, or liquid, or, in general case, matter) goes out of the frame of this paper. In any case, the conception of quark–gluon plasma allows demonstrably to explain the influence of new interaction on various phenomena observed at very high energies.