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ELEMENTARY PARTICLES AND FIELDS
Experiment

Prospects for Solving the Muon Puzzle on the NEVOD-DECOR-TREK Complex

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Abstract—The muon puzzle is an excess of muon bundles generated by primary cosmic rays (PCR) at energies above 10^{17} eV compared to estimations that assume even a heavy composition of PCR. The appearance of such excess of muons can be caused both by cosmophysical (the change in the spectrum and composition of cosmic rays) and nuclear-physical (the changing features of the hadron interaction) reasons. To separate these two possibilities it is necessary to measure energy characteristics of muon bundles and their dependence on energy of primary particles. Today the complex NEVOD-DECOR is the only one for such type experiment conduction. To improve the conditions of this experiment a further development of the experimental complex is planned: construction of new coordinate-tracking detector TREK for increasing of the area and improving of spatial resolution of muon track detection, modernization of the Cherenkov water detector for optimization of its structure and improvement of accuracy of energy deposit of muon bundle measurement, inclusion of the installation NEVOD-EAS in the experiment for independent evaluation of primary particle energy.

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1. INTRODUCTION

The concept of "muon puzzle" was formed in the second decade of the XXI century on the basis of generalization of the results of numerous experiments on the study of the muon component of EAS in experiments of various types [1]. It became widespread after the publication of the results of the WHISP working group, created to analyze the carried out experiments [2]. A decisive contribution to the formation of the muon puzzle was made by the NEVOD-DECOR experiment, in which a continuous increase in the excessive muon bundle intensity was obtained at energies above 10^{17} eV, exceeding the calculated values for any model of hadronic interaction and any composition of primary cosmic rays (PCR) [3, 4]. Numerous attempts to explain the muon puzzle due to changes in interaction models, mutual energy calibration of the results of various experiments, and others, slightly changed the position of the experimental points relative to the calculated curves, but did not explain the muon puzzle—the excess of EAS muon bundles growing with the energy of primary particles.

There are two possibilities to explain the muon excess: the first is a change in the characteristics of the PCR (energy spectrum and/or mass composition), and the second is a change in the characteristics of hadronic interaction with the inclusion of a new muon generation process (the creation of new heavy particles or the formation of a new state of matter, decaying, for example, into heavy quarks). The experimental separation of these hypotheses is associated with the study of the energy characteristics of muon bundles. To perform such an experiment, two independent detectors are needed: one for measuring the number of muons in a bundle, and the other for measuring their energy deposit. At present, only NEVOD-DECOR complex can be used for this purpose.

2. THE MAIN RESULTS OBTAINED AT NEVOD-DECOR EXPERIMENT

NEVOD-DECOR complex (Fig. 1) has an area of 100 m^2, but provides the possibility to investigate muon bundles generated by PCR in the widest region 3×10^{14}–3×10^{18} eV due to registration of inclined EAS. The experimental complex includes the Cherenkov water calorimeter (CWC) NEVOD [5, 6] and the coordinate-tracking detector DECOR [7]. Registration of muon bundles in a wide range of multiplicity and zenith angle provides a possibility to study cosmic rays in a wide range of primary energies in the framework of a single experiment. The

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CWC NEVOD with a volume of 2000 m^3 contains a spatial lattice of quasispherical modules (QSM). The DECOR detector with a total area of about 70 m^2 includes eight supermodules (SM) located in the galleries of the NEVOD building on three sides of the water tank. The sensitive area of each supermodule is 8.4 m^2. Supermodules consist of eight vertical planes of plastic streamer tubes with a resistive cathode and an external two-coordinate readout strip system.

Long-term series of registration of muon bundles with a multiplicity of more than three parallel particles in the range of 30°–90° were carried out with a total ~78000 hours of exposition in 2002–2008 and 2012–2021 [8, 9]. The range 30°–55° was studied to determine the minimum zenith angle at which the contribution of the electronic and hadronic components of the EAS to the registered events with muon bundles becomes negligible.

The distribution of the registered events in multiplicity and zenith angle, which covered 5 orders of magnitude in the number of events, demonstrated the possibility of studying muon bundles from primary particles in the range of three to four orders of magnitude in energy [8].

To match the registered muon bundles to the energies of primary particles, a method of local muon density spectra (LMDS) [8] was developed, with the help of which a relationship was established between the energy of an EAS (primary particle), the local muon density, and the zenith angle:

$$\langle\log(E, \mathrm{GeV})\rangle \approx 7.03 + 1.07\log\left(D, \mathrm{m}^{-2}\right) + 3.80\log(\sec\theta). \quad (1)$$

Using the LMDS method, according to the results of the first series of experiments, it was found that at angles of ~30° in the energy range of 10^{15}–10^{16} eV, the experimental points correspond to the normal composition of cosmic rays, and in the middle of this interval there is a well-known knee in the energy spectrum. At angles of ~50° in the energy range above 10^{16} eV, the experimental points are observed to approach the results of calculations for a purely iron composition of PCR. At angles of ~65° in the energy range ~10^{17} eV, the second knee in the energy spectrum is observed with a change in the slope $\Delta\gamma \sim 0.2$ for a purely iron composition of the PCR. At angles of 78° in the energy range of ~10^{18} eV and higher, the experimental points exceed the calculated curves for a purely iron PCR composition for any interaction models.

According to the results of the second series of measurements, it was demonstrated that an increase in the multiplicity (local density) of muons is observed at all zenith angles and at energies of ~10^{17} eV begins to exceed the results of calculations for a purely iron composition of PCR for any interaction models.

The results obtained in the NEVOD-DECOR experiment [8] were confirmed in the experiments of Pierre Auger (2013) [10] and IceCube (2018) [11]. The good agreement of these results, obtained at different installations and by different methods, not only in the energy dependence, but also in the absolute value of the muon excess, testifies to the reliability of the results obtained.

To solve the muon puzzle, an experiment was started to measure in the Cherenkov water detector NEVOD the energy release of muon bundles registered by the coordinate detector DECOR. Energy of muon component of EAS was almost uninvestigated till present, despite of the fact that it is the only characteristic that responds differently to a change in the composition of cosmic rays and to the inclusion of new physical processes. Figure 2 shows the possible behavior of EAS muon energy deposit above the knee if the composition becomes heavier (lowest line), the new processes of muon generation appear (highest line) or the composition stays the same (mid line).

Such measurements can give the only experimental answer for the reasons of the muon excess. Currently the NEVOD-DECOR complex is the only facility in the world on which such experiment can be carried out, since two different detectors are required: one for registration of the number of muons (DECOR) and another for their energy deposit measurements (NEVOD).

Figure 3 shows the last published [12] dependence of the muon bundle average specific energy deposit on the local muon density for zenith interval 55°–65°. The arrows indicate the calculated mean logarithmic values of primary particle energies [8]. The last points lie above the line for the simulated muon spectra for the pure iron composition of the primary cosmic ray spectra. Large errors at energies >10^{17} eV are caused not only by small statistics.

The existing coordinate-tracking detector DECOR does not cover the entire aperture of the Cherenkov water detector and does not exclude the possibility of passing of part of the muons through the gaps between individual detector modules, and its cells limit the possibility of separating two or more particles by a distance of 3 cm. This leads to a restriction on both the maximum multiplicity of the studied bundles (and the upper energy limit) and on its minimum (due to the low area and large distance between the modules of the detector DECOR). Additionally Cherenkov water detector has not optimal structure and can give different responses at muon bundles going through various places of it.

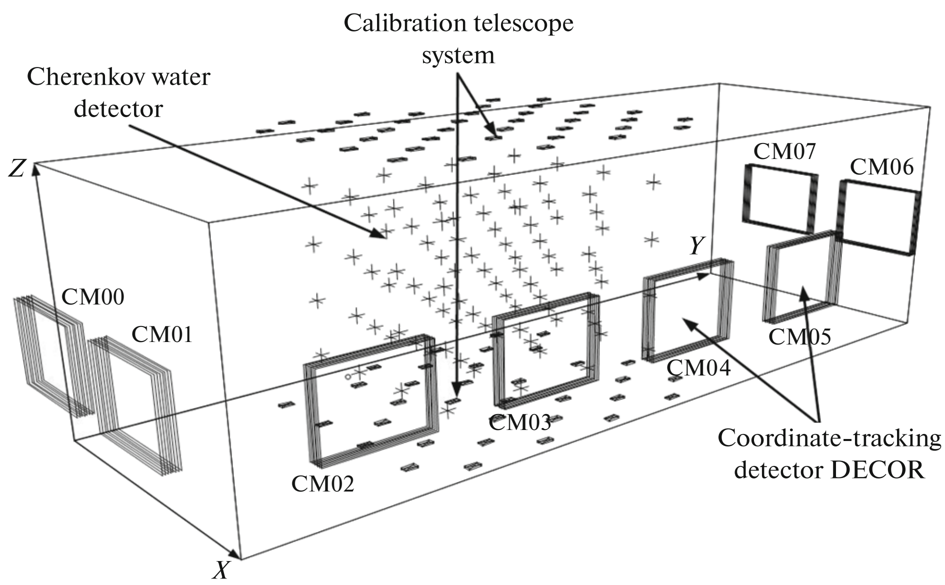

Fig. 1. Layout of the NEVOD-DECOR experiment.

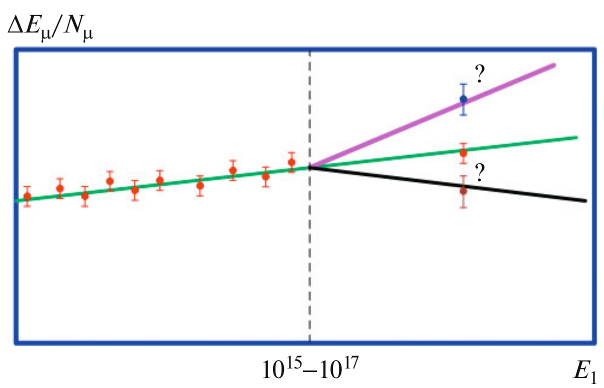

Fig. 2. Possible behavior of the EAS muon bundles' energy deposit above the knee.

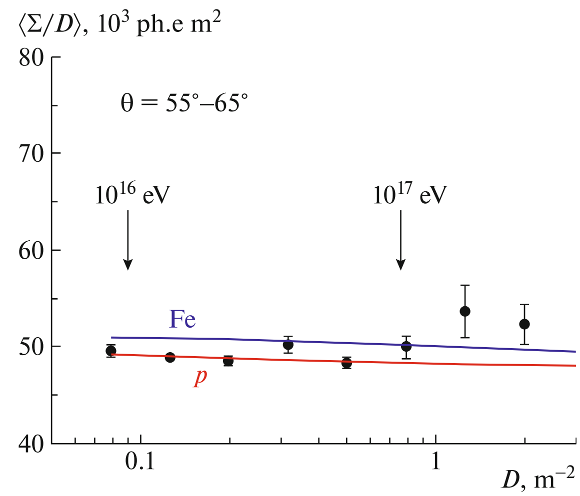

Fig. 3. Dependence of the muon bundle average specific energy deposit on local muon density for zenith interval 55°–65° [10]. Points are experimental data; curves represent the expected dependence based on the simulations with CORSIKA for primary protons (p) and iron nuclei (Fe); arrows indicate the characteristic energies of primary cosmic ray particles.

3. FURTHER DEVELOPMENT OF EXPERIMENTAL COMPLEX NEVOD FOR MUON PUZZLE SOLUTION

To achieve the best conditions for muon puzzle solution three serious changes in the Experimental complex NEVOD are planned: construction of the coordinate-tracking detector TREK consisting of drift chambers, modernization of the Cherenkov water detector to provide the better accuracy for muon bundle energy deposit measurements and inclusion in the experiment of NEVOD-EAS array for independent evaluation of the energy of cosmic ray generating muon bundles.

To check a possibility to use drift chambers for muon bundle detection a small coordinate-tracking unit from drift chambers (CTUDC) was constructed. The successful solution of the tasks assigned to CTUDC [13] opened the possibility of creating a large installation based on multi-wire drift chambers, capable of reconstruction of dense muon bundles and having an area sufficient to overlap the entire side of the Cherenkov water detector.

The coordinate-tracking detector TREK [14] will have an effective area of 250 m^2 and consist of 264 multi-wire drift chambers forming two planes at the outer wall of CWC (Fig. 4). Planes differ in the chamber orientation: in outer plane DC are near-vertical, in another plane DC are horizontal. The

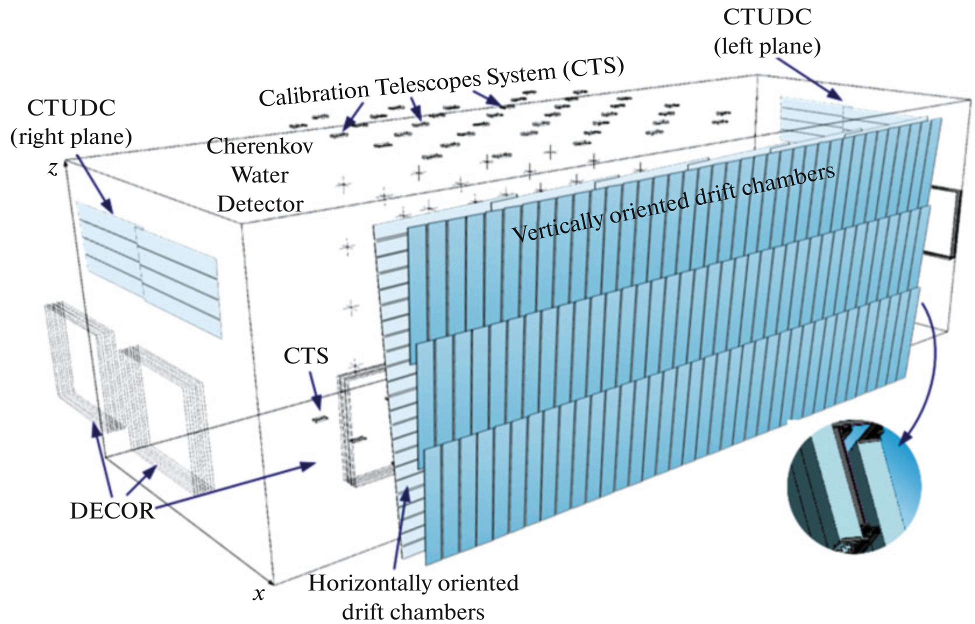

Fig. 4. Coordinate planes of the TREK detector at the long side of the Cherenkov water detector.

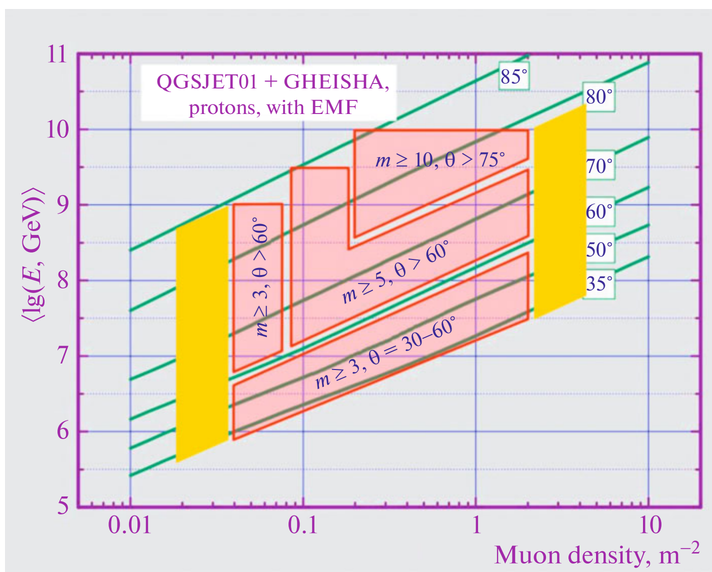

Fig. 5. Results of calculating the average logarithms of the energy of primary particles responsible for events with a local muon density D for different zenith angles. Polygons—areas corresponding to the selection of bundles of different categories in the DECOR experiment.

detector is settled in a special box that has been built in 2019.

Drift chambers provide a high resolution of close tracks for cosmic ray experiment (3 mm) that is 10 times better than DECOR. This allows to reconstruct events with average density of particle tracks up to 10 per m^2. The full coverage of the side wall of Cherenkov water detector provides less uncertainty in estimation of the number of particles that passed through the water volume. That is especially important for low density events. The use of the new detector will expand the energy region of the complex NEVOD-DECOR-TREK to 10^{14}–10^{19} eV (Fig. 5) and will decrease statistical and systematical errors in estimation of the muon energy deposit.

Current configuration of the Cherenkov water detector (Fig. 6) is not symmetrical with respect to water volume and the distance between 91 measuring quasi-spherical modules is small. After the launch of a new water purification system the transparency

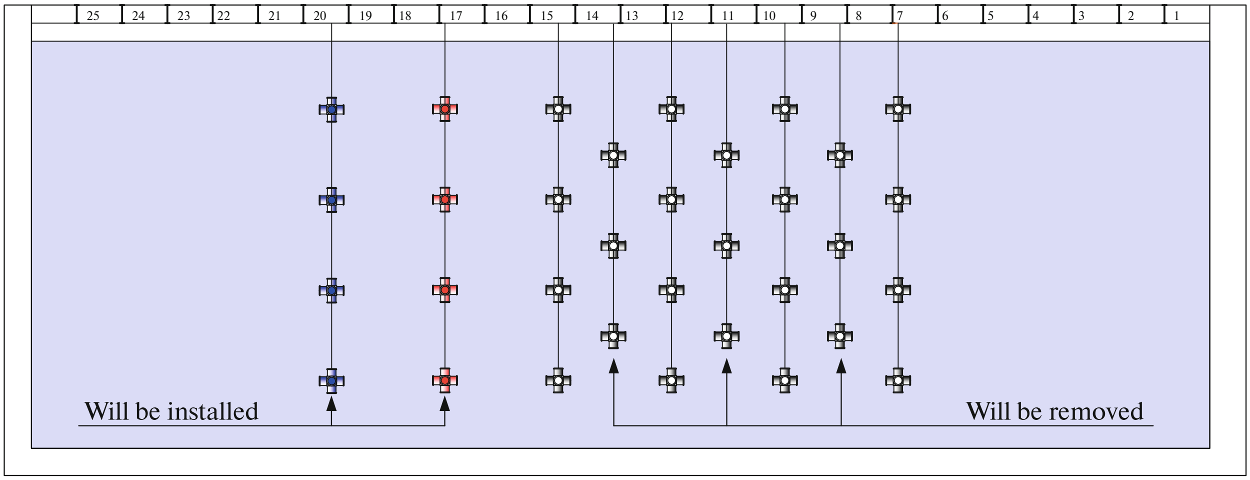

Fig. 6. The lattice of Cherenkov water detector measuring quasi-spherical modules (QSM) after extension.

dramatically increased and now it is possible to make 96 modules enlarged for more symmetrical lattice. Also 32 QSM will use custom Hamamatsu photomultipliers R877 (the old ones used FEU-200) and different readout electronics [15]. Such configuration will simplify energy deposit measurements and will decrease errors.

The energy of primary particles responsible for generation of registered muon bundles in NEVOD-DECOR and NEVOD-DECOR-TREK experiment can be evaluated by formula (1). However this formula is good only in average. To check this formula, independent evaluation of primary particle energy is required. For this, the new NEVOD-EAS array was constructed [16].

The main task of the NEVOD-EAS array is to detect the electron–photon component of extensive air showers (EAS) in the energy range of primary particles from 10^{15} to 10^{17} eV both independently and in conjunction with other detectors and facilities of the Experimental complex NEVOD, and reconstruct EAS size (accuracy of $\sim$40%), core position (accuracy of $\sim$5 m) and arrival direction (accuracy of $\sim 3^\circ$). The present configuration of the array (launched into operation in 2018) includes 9 clusters of scintillation detector stations which are deployed around the Experimental complex NEVOD over the area of about 10^4 m^2. Each cluster, containing 4 scintillation detector stations and a local registering system, represents an independent EAS detector measuring the number of particles (up to 25000 particles) and their arrival time (3 ns accuracy) with each detecting element. All clusters are combined with the hardware and software system ensuring their synchronous (10 ns accuracy) operation, data acquisition and storage of experimental information.

4. CONCLUSION

Investigations of muons in inclined EAS up to horizon allow to study cosmic ray energy spectrum in a very wide interval from 10^{14} to 10^{18} eV and even higher. The main contribution to revealing the muon puzzle comes from the experiment NEVOD-DECOR, in which the energy interval was 3×10^{14}–3×10^{18} eV. The main possibilities of muon puzzle solution may be cosmophysical (change of energy spectrum or/and mass composition of primary cosmic rays) and nuclear physical (change of model of hadron interaction). To separate these two possibilities it is necessary to measure the energy characteristics of muon bundles. Today NEVOD-DECOR complex is the only one in the world for solution of this task, since the solution requires separate measurements of the number of muons (DECOR) and their energy deposit (NEVOD). The first results of this experiment show an evidence in favor of a change of the interaction model.

But limitations of NEVOD-DECOR complex cause large systematic uncertainties in the region higher than 10^{17} eV. The new coordinate-tracking detector TREK will cover the full side wall of the Cherenkov water detector (its area will be 7 times larger than DECOR) and will have two-track resolution about 3 mm (10 times better than in DECOR). The modernization of the Cherenkov water detector NEVOD will allow to have the symmetrical structure of the detecting system, which will increase the accuracy of energy deposit measurements. We hope that after these improvements of the experimental complex the muon puzzle will be solved. Inclusion in the Experimental complex of the new NEVOD-EAS array will give a possibility to evaluate the energy of each primary particle that generated muon bundle.

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