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New technique and results of cosmic ray investigations in the energy interval 10^{15}–10^{19} eV

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Abstract. New technique of EAS investigations based on the measurements of local muon density spectra (LMDS) is developed. Application of this method to investigations of inclined EAS allows exploration of CR energy interval from 10^{15} to 10^{19} eV by means of a relatively small detector with area $\sim 100\,\text{m}^2$ due to very strong dependence of EAS muon density on zenith angle. During 2002–2007, long-term NEVOD-DECOR experiment (about 20,000 h live time) was conducted, and more than two million muon bundles in zenith angle interval 30–88 degrees were registered. Comparison of experimental data with results of CORSIKA-based simulations showed that the new method is sensitive to all main peculiarities of CR energy spectrum: the knee, increase of the energy spectrum slope with energy, the second knee. But the observed progressive excess of muon bundles with the increase of primary CR energy in comparison with simulations (even for pure iron composition) can indicate the appearance of new processes of muon generation. In this case, for correct investigations of EAS, the experimental arrays must be supplemented by detectors which can measure or evaluate the energy of muons.

1. INTRODUCTION

This year coincides with 100 anniversary of cosmic ray discovery and more than 50 years from the first observation of the knee in EAS energy spectrum (more correctly, in the spectrum of EAS size in charged particles). During this period the following results above 10^{15} eV were obtained: the knee, steepening energy spectrum, the second knee, the ankle, GZK cut-off. All these results were obtained in frame of existing models of hadron interaction in which accelerator data are extrapolated up to upper limit of cosmic ray energies. At the same time, information about mass composition of cosmic rays is not so definite and often even contradictory. The reasons of these disagreements can be connected with different techniques of EAS detection and narrow energy intervals, which are accessible for each EAS array. From this point of view the development of new methods and approaches to EAS investigations is an important task.

At present, the following parameters of EAS are measured: number of electrons N_e (in fact, mixture of charged particles); number of muons N_μ (in fact, ionization effect in scintillation detectors, produced by muons and possible secondary particles); energy deposit of EAS core, E_h (in calorimeter measurements); fluorescence radiation flux, F_f; Cherenkov radiation flux, F_ch; radio emission flux, F_r (first results appeared recently); acoustic radiation flux, F_a (ideas of the use of this method are permanently discussed, but no real results were obtained). Two new methods are connected with EAS muon component investigations: local muon density, D_μ (which was realized in the NEVOD-DECOR

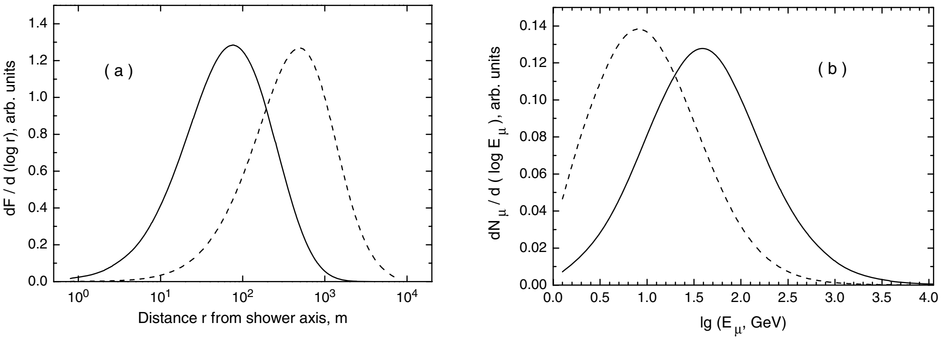

Figure 1. (a) Contribution of muons detected at various distances from the shower axis to the spectrum of events selected in particle density (solid curve) and to the total number of EAS muons (dashed curve); (b) energy spectra of all EAS muons (dashed curve) and muons detected in bundles (solid curve). Zenith angle $\theta = 60^\circ$.

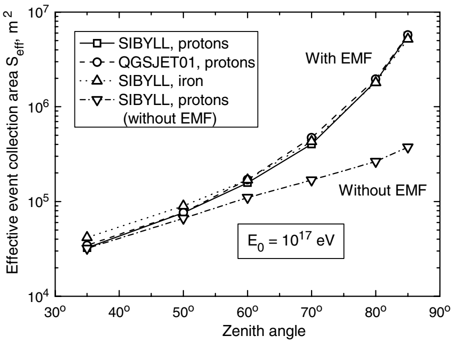

Figure 2. Zenith-angular dependence of effective EAS collecting area in LMDS method.

experiment); muon bundle energy deposit, $E_{\mu b}$ (the use of this method in NEVOD-DECOR experiment is planned).

2. METHOD OF LOCAL MUON DENSITY SPECTRA (LMDS) IN INCLINED EAS INVESTIGATIONS

The detailed description of LMDS method is given in paper [1]. Here the main advantages of this method in comparison with N_μ measurements are discussed. The first one is the range of distances from EAS axes which give basic contribution to total number of EAS muons estimated from N_μ measurements and to spectrum of events selected by muon density. Figure 1a illustrates this difference. It is seen that the main contribution to the local muon density spectrum give about ten times smaller distances from the EAS axes than to the total number of muons. Correspondingly, muon energies which give main contribution to LMDS and to the total muon number will be different, too. In Fig. 1b, energy spectra for these two cases are shown.

Of course, LMDS method can be used for any EAS arrival directions, but it is especially effective for investigations of inclined EAS. Due to a strong dependence of characteristics of the Earth's atmosphere on zenith angle, the lateral size of EAS muon component rapidly increases, and the shower may be detected at large distances from the axis, so that the region from which such events are collected is determined in this case by the cross-sectional area of the shower rather than by the detector size (Fig. 2). As can be seen, at large zenith angles very important role in the increase of the collecting area plays the

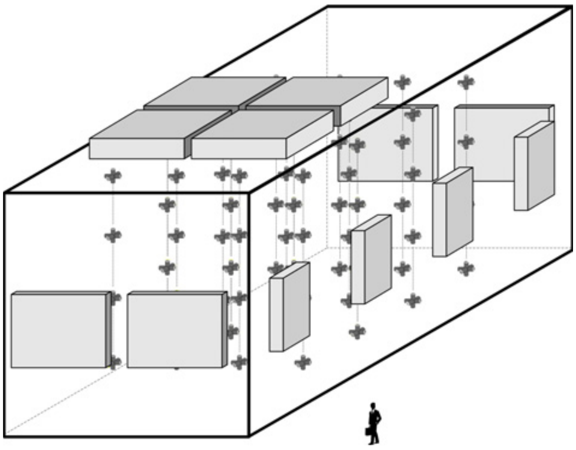

Figure 3. Layout of the NEVOD–DECOR experimental array (for description, see the main body of the text).

geomagnetic field (EMF). Therefore at detecting nearly horizontal muon bundles this area (more than 1 km^2) is sufficient for obtaining statistically significant results up to primary particle energies of 10^{18} eV and even higher. In this situation, the muon bundle detector with sizes of several tens square meters can be considered as a point-like device.

3. NEVOD-DECOR EXPERIMENT

The layout of experimental complex NEVOD-DECOR is presented in Fig. 3. It consists of two main detectors. The DECOR coordinate detector [2], which is a multilayer system of plastic streamer tubes featuring resistive coating of the cathode, is deployed around the NEVOD Cherenkov water calorimeter [3] of internal volume $9 \times 9 \times 26\,\mathrm{m}^3$. The DECOR side part, placed in the gallery of the building on the three sides of the NEVOD tank, includes eight supermodules of working area 8.4 m^2 each, which consist of eight vertical planes of streamer tubes hung at a distance of 6 cm from one another. The upper part of the coordinate detector consists of four supermodules 11.5 m^2 in area each, which are mounted on horizontal platforms. The DECOR planes involve an external two-coordinate readout system from aluminum strips, which ensures determination of positions of charged-particle tracks to a precision about 1 cm in each of the coordinates (X, Y). The angular precision in reconstructing muon tracks intersecting supermodules is about 0.7° and 0.8° for projected zenith and azimuth angles, respectively. The detecting system of the NEVOD calorimeter is a spatial lattice of quasi-spherical measuring modules (crosses in Fig. 3), which make it possible to detect Cherenkov radiation from relativistic charged particles in water from any direction, to estimate the energy deposition in the detector volume, and to reconstruct the direction of motion of these particles. The total "live" time of operation of the array with fully equipped DECOR side part (eight supermodules, the set of triggering event-selection conditions being invariable) was 19,922 h. An example of an event with a muon bundle in the coordinate detector is presented in Fig. 4.

Results of selection of muon bundles with various multiplicities and zenith angles are given in Table 1. Since the detected number of muon bundles with small multiplicity and low zenith angles is very large, for the analysis only a part of total statistics was taken. In Fig. 5, the regions of primary energies and zenith angles which correspond to the obtained experimental data (Table 1) are shown.

For these events, the spectra of local muon density were obtained, which are compared with results of calculations by means of the CORSIKA code [4] under various assumptions on the spectrum and composition of primary cosmic rays and on hadron interaction models (Fig. 6). From the figure, the

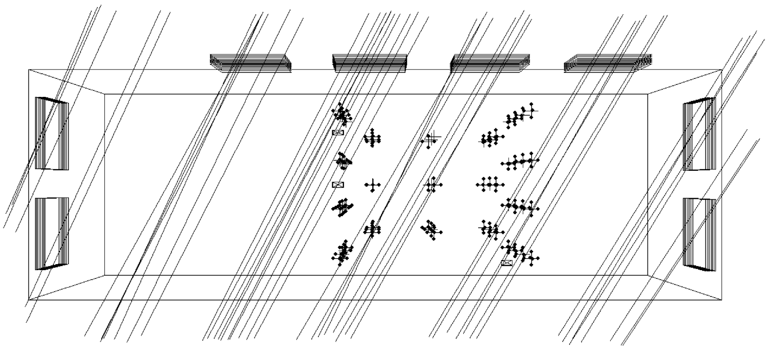

Figure 4. Results of geometric reconstruction of the event with 50 quasi-parallel tracks, the zenith angle being 78° (projection onto the horizontal plane of the detector).

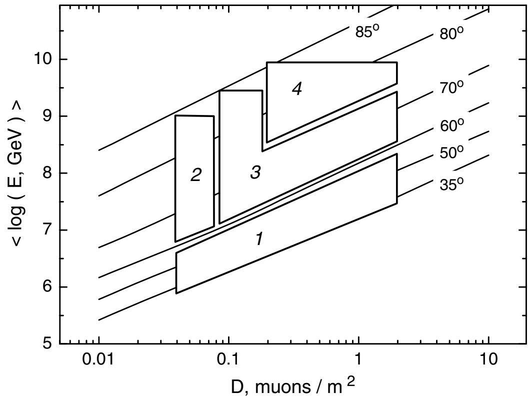

Figure 5. Average logarithms of the energy of primary particles responsible for events with different local muon densities D for various zenith angles. The polygons correspond to categories of events indicated in Table 1.

Table 1. Statistics of selected muon bundles.

Category of events	**Muon multiplicity**	**Zenith angle range**	**Live time, (hour)**	**Number of events**
1	≥ 3	30 – 60°	758	18137
2	≥ 3	$\geq 60°$	1552	4109
3	≥ 5	$\geq 60°$	10102	6786
4	≥ 10	$\geq 75°$	19922	395

following conclusions can be done. At energies between 10^{15} and 10^{16} eV the first knee is observed and mass composition is nearly normal (as measured at lower energies). In the energy interval 10^{16}–10^{17} the spectrum of local muon density moves to the prediction for pure iron composition and at higher energies corresponds to this composition. At that, the second knee at energy about 10^{17} eV is observed. At energies about 10^{18} eV, the experimental LMDS is higher than predicted ones.

To compare the obtained results with other experimental data at these energies, the LMDS were converted into primary spectra by using traditional assumptions about composition and interaction of UHECR. The results are given in Fig. 7.

One can see that estimations of primary spectrum on the basis of DECOR data are incompatible with HiRes, Auger and TA data (even under assumption of iron composition). If we assume that the energy

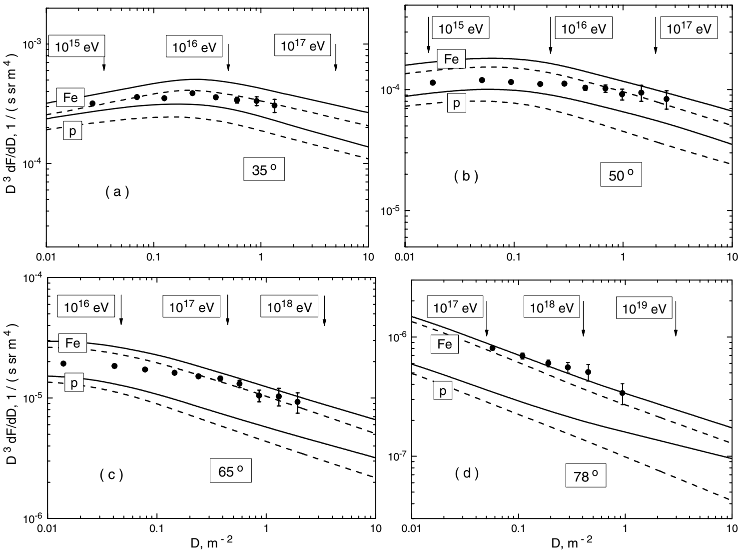

Figure 6. Experimental and calculated differential spectra of the local muon density at zenith angles of (a) 35°, (b) 50°, (c) 65°, and (d) 78°. Points represent experimental data; the solid and dashed curves correspond to results of calculations performed by using the QGSJET01 and SIBYLL2.1 models, respectively. In each panel, the lower pair of curves corresponds to primary protons, while the upper pair corresponds to iron nuclei.

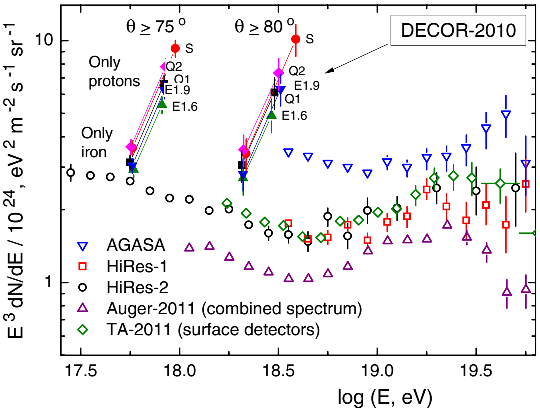

Figure 7. Differential spectrum of primary cosmic rays at ultra high energies. The closed symbols stand for the intensity reconstructed on the basis of DECOR data for two limiting assumptions on the composition of primary cosmic rays (protons and iron nuclei) by using the SIBYLL2.1, QGSJET01, QGSJET-II, EPOS1.61 and EPOS1.99 hadron-interaction models (S, Q1, Q2, E1.6 and E1.9 labels at the points). The open symbols represent well-known data (boxes) HiRes-1 [5], (circles) HiRes-2 [5], (inverted triangles) AGASA [6], (triangles) PAO [7] and (diamonds) TA [8] results.

calibration of the fluorescent method used by HiRes and PAO collaborations is close to a true one, then results presented in Fig. 7 indicate inapplicability of aforementioned interaction models in calculating the properties of the muon component of extensive air showers in the energy region around 10^{18} eV. In order to explain the observed intensity of muon bundles at large zenith angles, one needs considerably higher (by a few tens of percent) muon density in the shower central region.

4. DISCUSSION

Application of the new approach to studying extensive air showers that is based on measuring spectra of the local muon density at various zenith angles makes it possible to obtain information about the properties of the flux and interaction of cosmic rays over a broad range of primary particle energies (which covers more than three orders of magnitude) within a single technique by using the same experimental facility of relatively small size. The spectra of the local muon density are sensitive to the shape of the primary spectrum, the mass composition of primary cosmic rays, and the properties of the interaction of ultrahigh-energy hadrons in the forward kinematical region, where the uncertainties in the existing theoretical models with increasing of energy are maximal.

An analysis of the DECOR experimental data on muon bundles which is based on the comparison of the measured local muon density spectra with the results of simulation performed by using the CORSIKA code indicates that the muon density increases gradually in relation to the value expected for a fixed composition of primary cosmic rays. A probable interpretation of this is that the composition becomes heavier.

But the measured intensity of muon bundles produced in extensive air showers by primary particles of energy about 10^{18} eV at large zenith angles is significantly higher than that which could be expected on the basis of data obtained for primary cosmic rays by the fluorescence method even for pure iron composition and any extensively used models of hadron interactions.

Of course, it is possible to develop a model of hadron interaction which will give higher multiplicity of secondary particles in the forward region to explain obtained experimental data. But there are some evidences that excess of muons exists at very high energies [9, 10]. To explain these data, serious changes of interaction model are required, including a new physical process appearance.

5. CONCLUSION

Since the main task of the Symposium is discussion of further development of UHECR investigations, it is possible to do the following conclusion: new experiments must give a possibility to evaluate muon energy in detected EAS.

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