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New approach to UHE cosmic ray investigations in the energy range 10^{15} - 10^{19} eV

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Abstract: A new approach to investigations of UHE cosmic rays based on the ground-level measurements of the spectra of local density of EAS muons at various zenith angles is considered. It is shown that muon density spectra are sensitive to the primary cosmic ray spectrum and composition, and to features of the forward kinematical region of hadronic interaction. New experimental data on muon bundles at zenith angles from 30° to horizon obtained with the coordinate detector DECOR are compared with CORSIKA-based simulations. It is found that measurements of muon density spectra in inclined EAS give possibility to study characteristics of primary cosmic ray flux in a very wide energy range from 10^{15} to 10^{19} eV.

Introduction

At energies above 10^{15} eV, the only source of information on primary cosmic rays and their interactions are extensive air showers (EAS) detected at the Earth's surface. However, in spite of significant progress in experimental technique during last 50 years main puzzles of primary CR spectrum (slope, composition, "knee", "ankle", GZK cutoff) are not sufficiently understood till now. A quantitative interpretation of observational results is model dependent and EAS analysis involves many unknown functions: primary CR energy spectrum and composition, extrapolation of hadronic interaction description into UHE and EHE region, and others. Therefore extension of a set of different EAS observables is desirable. In present paper, an approach to investigations of UHE cosmic rays based on a new EAS observable - local density of EAS muons - is considered. Spectra of local muon density are sensitive to primary spectrum and composition and are formed by the central part of the shower, hence carrying information about early stages of shower development [1].

Local muon density phenomenology

The idea of a new approach is to study local density spectra (LDS) of EAS muons at different zenith angles. At large angles transverse area of showers (mainly muons at ground level) exceeds square kilometers. Hence, muon detector may be considered as a point-like probe and capability of UHE primary particles detection is determined not by size of the setup but by effective EAS dimensions in plane orthogonal to the axis. In this case the observed muon bundle multiplicity m is related to the local muon density D (measured in particles/m^2) as $D \sim m / S_{det}$. Contribution to the flux of events with a fixed local density is given by showers with different primary energies detected at different distances from the axis; however, due to a fast decrease of cosmic ray flux with the increase of energy, the effective interval of primary particle energies appears relatively narrow [2]. Fixed muon densities at different zenith angles correspond to substantially different primary energies; at that, event collection area increases with zenith angle. It provides a unique possibility to study CR characteristics in a very wide range of primary energies. Without taking into account fluctuations of the shower development, the integral spectrum of the events in local density may be written as:

$$F(\geq D) = \int_0^\infty N(\geq E(\vec{r}, D))dS, \quad (1)$$

here $\vec{r}$ is the point in the transverse section of the shower, $N(\geq E)$ is the integral primary energy spectrum, and the minimal energy E is defined by the equation $\rho(E, \vec{r}) = D$, where $\rho(E, \vec{r})$ is muon LDF in a plane orthogonal to the shower axis. As it is seen from the dimensions in eq. (1), the integral local muon density spectrum is expressed as the number of events per unit solid angle and time interval. Assuming a nearly scaling behavior of muon LDF around some primary energy E_0, it may be parameterized as $\rho(E,\vec{r})=(E/E_0)^{\kappa} \cdot \rho(E_0,\vec{r});\ \kappa \approx 0.9,$ and for a power type primary energy spectrum $N(\geq E) = A(E/E_0)^{-\gamma}$ we obtain an approximate expression for the local muon density spectrum:

$$F(\geq D) = A \cdot D^{-\beta} \int [\rho(E_0, \vec{r})]^{\beta} dS; \beta = \gamma / \kappa. \quad (2)$$

Thus, in frame of these approximations the muon LDS exhibits a power type behavior, a slope being somewhat steeper than that of primary particles. Similar to the spectrum of EAS in the total number of muons N_μ, it increases in absolute intensity for heavier nuclei. The distinctive feature of the muon LDS is that it is sensitive to the shape of the muon lateral distribution, since in the integrand of eq. (2) the LDF enters with index $\beta \sim 2$. Thus, selection of the events by muon density enhances the sensitivity of measured distributions to the central part of the shower. High-energy muons propagating near the axis are probes of the early stages of shower development that are governed by high-energy hadronic interactions.

Experimental

Possibilities of the new approach may be illustrated by local muon density spectra obtained on the basis of the data on muon bundles accumulated during experimental runs with the NEVOD-DECOR complex in 2002 – 2006 (16668 hours live time). The coordinate detector DECOR [3] represents a modular multi-layer system of plastic streamer tube chambers with two-coordinate external strip readout, arranged around the Cherenkov water calorimeter NEVOD [4]. The side part of DECOR includes eight 8-layer assemblies (supermodules, SM) of chambers with the total sensitive area 70 m^2. Angular accuracy of reconstruction of muon tracks crossing the SM is better than 0.7° and 0.8° for projected zenith and azimuth angles, respectively. The event selection procedure includes several stages: trigger selection; soft program selection; scanning of muon bundle candidates, final event classification, and track counting by operators. To suppress the residual soft EAS component, for angles < 75° only events in limited intervals of azimuth angle (with DECOR SMs shielded by the water tank) are selected. It gave possibility to select muon bundles starting from 30° and from a minimal multiplicity determined by trigger conditions ($m \geq 3$).

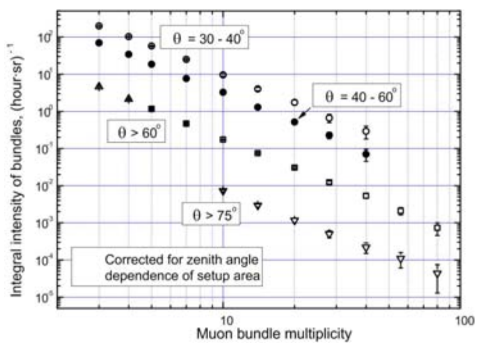

Figure 1: Integral distributions in muon bundle multiplicity for different zenith angle intervals

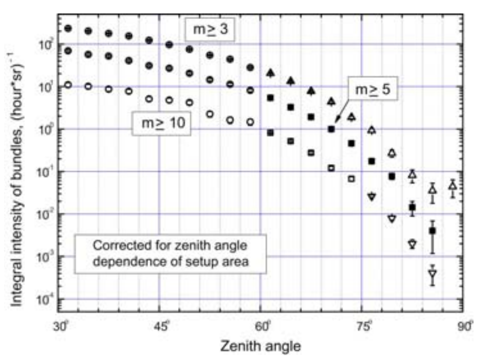

Figure 2: Distributions in zenith angle for different minimal muon bundle multiplicity

Experimental statistics used in present analysis were selected in different zenith angle and multiplicity intervals, corresponding to different ranges of primary energy. In Figure 1, the integral distribution in muon bundle multiplicity for different zenith angle intervals is shown. The distribution in zenith angle for different minimal muon bundle multiplicity is presented in Figure 2. Different symbols correspond to different data subsets. As a whole, experimental muon bundle data cover about 6 – 7 decades in event intensity.

General scheme of data analysis includes: selection of muon bundle events and construction of distributions in muon bundle multiplicity and angles; iterative deconvolution of the measured distributions to detector-independent spectra of local muon density for several zenith angle intervals; simulation of muon LDF for different types of primary particles, energies, and hadronic interaction models by means of the CORSIKA code; calculation of the expected muon LDS by means of the convolution of LDF with a certain primary spectrum and composition model.

Reconstruction of muon LDS from the observed characteristics of muon bundles is started from estimation of parameters of a spectrum model in a following semi-empirical form:

$$dF_0(D,\theta)/dD = C \cdot D^{-(\beta+1)} \cos^{\alpha}\theta. \quad (3)$$

A power-type dependence of the muon LDS follows from the analytical consideration given above (eq. 2). On the other hand, analysis of zenith angle distributions of muon bundles detected in DECOR has shown that these distributions are well described by power function of zenith angle cosine [5]. Procedure of experimental estimation of muon LDS in more detail is described in [1].

Simulation details

Muon LDFs in a plane orthogonal to the shower axis were calculated on the basis of CORSIKA code (v. 6.500) [6] for fixed zenith angles, a set of primary energies (from 10^{14} to 10^{19} eV, one point per decade), pure protons and pure iron nuclei as primary particles, and two combinations of hadron interaction models: QGSJET01c + GHEISHA2002 and SIBYLL2.1 + FLUKA2003.1b. Calculations have been performed with consideration of the Earth magnetic field, which significantly decreases muon density in the central part of the shower [7] and influences the intensity of events selected by muon density [8]. As a reference model of the primary flux, a power type all-particle differential spectrum in the form dN/dE = 5.0 × (E, GeV) $^{-2.7}$ cm^{-2} s^{-1} sr^{-1} GeV^{-1} below the knee energy, steepening to (γ + 1) = 3.1 above the knee (4 PeV) was used. This spectrum is close to MSU data as given in [9].

In Figure 3, results of calculations of the average logarithms of the energy of primary particles that give contribution to events with a given local muon density D for several zenith angles (labels near the curves) are presented. The polygons in the figure outline the regions corresponding to selection of muon bundles of different categories. The lower limit of accessible primary energies corresponds to about 10^{15} eV because of low muon densities in such EAS. On the other hand, statistical limitations appear around 10^{19} eV, since the number of detected events with such muon densities and angles becomes low.

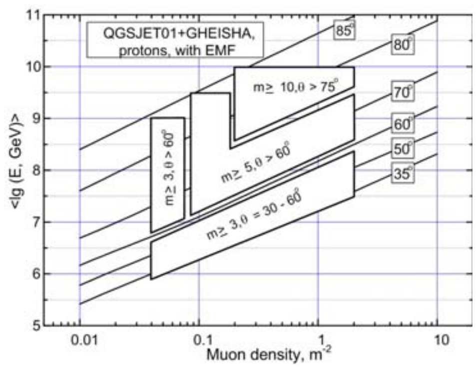

Figure 3: Average logarithms of primary energies responsible for events with a given local muon density for various zenith angles (see the text)

Results and discussions

The measured and calculated differential muon LDS multiplied by D^3 for zenith angles 35°, 65° and 78° are presented in Figure 4. The points are obtained from different sub-sets of the experimental data. The curves correspond to calculation results for two extreme versions of primary composition (only protons and only iron). A reasonable agreement (including the absolute normalisation) of the present data with CORSIKA-based simulation is observed. At moderate zenith angles (35°), the steepening of the spectra related with the knee is seen. Data for 65° correspond to intermediate primary energies (about 3 – 500 PeV). In this angular interval, the behavior of experimental LDS demonstrates a trend to a heavier composition and a hint for an increase of the slope near 10^{17} eV: partial fits of the data above and below this energy (thin lines in the figure) give $\Delta\beta = 0.20 \pm 0.10$. Large multiplicity events in the last angular interval ($m \geq 10$, $\theta > 75°$) correspond to energies around 10^{18} eV. In order to confront DECOR data with other experiments, we have calculated expected muon density spectra for two models of primary spectrum, based on HiRes and AGASA results [10] in the range 10^{18} - 10^{19} eV.

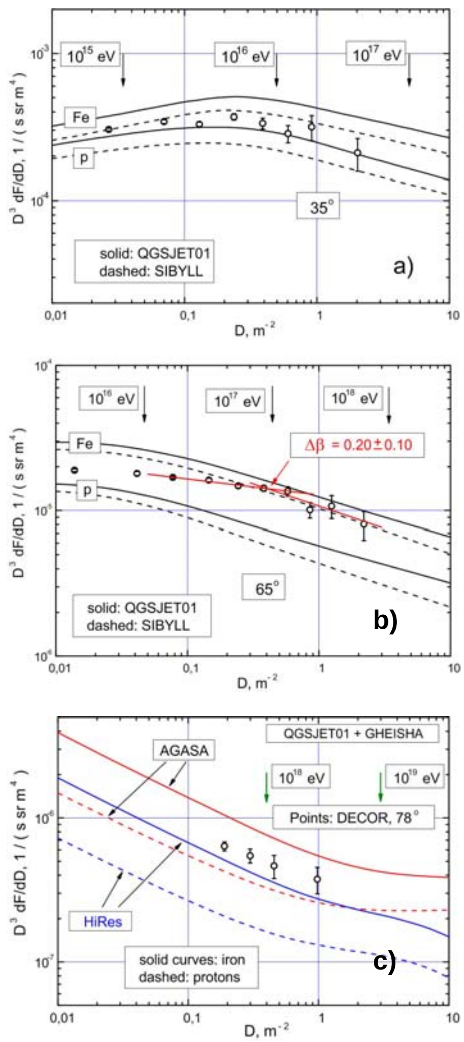

Figure 4: Muon LDS for different zenith angles. Points - DECOR data; curves - calculations. a) θ = 35°; b) θ = 65°; thin lines represent partial fits of the data below and above 10^{17} eV; c) θ = 78°; the curves correspond to HiRes-based and AGASA-based models of primary spectrum

Both these measurements give a similar spectrum shape in this energy range, clearly showing an ankle feature (though shifted in energy), however disagree (about two times) in normalisation. The curves shown in Figure 4c were obtained with QGSJET01 interaction model; SIBYLL predicts somewhat lower absolute intensity. As seen from the figure, in frame of these models the measured muon LDS does not contradict AGASA data under assumption of a mixed composition, and is not compatible with HiRes-based intensity.

Conclusion

The approach based on a new phenomenological variable – local muon density – gives possibility to investigate characteristics of primary cosmic ray flux in a very wide energy range (from the knee to the ankle) by means of a single detector of relatively small area with the same experimental technique. Muon LDS are sensitive to primary spectrum and composition and forward region of hadronic interactions. Analysis of muon LDS together with data on other EAS observables will allow putting new constraints on combinations of spectrum, composition and interaction models.

Acknowledgments

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References

[1] N.S.Barbashina et al. Nucl. Phys. B (Proc. Suppl.) 165 (2007) 317.
[2] I.I. Yashin et al. Proc. 28th ICRC, Tsukuba, 3 (2003) 1147.
[3] M.B. Amelchakov et al. Proc. 27th ICRC, Hamburg, 3 (2001) 1267.
[4] V.M. Aynutdinov et al. Astrophysics and Space Science, 258 (1998) 105.
[5] I.I. Yashin et al. Proc. 29th ICRC, Pune, 6 (2005) 373.
[6] D.Heck et al. http://www-ik.fzk.de/corsikaT
[7] M.Ave et al. Astropart. Phys., 14 (2000) 19.
[8] A/G/Bogdanov et al. These proceedings, paper ID 0203.
[9] S. Eidelman et al. Phys. Lett., B592 (2004) 1.
[10] R.U. Abbasi et al. arXiv:astro-ph/0703099v1 (March 2007).