Investigation of EAS electron and muon components by means of the NEVOD calibration telescope system

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Abstract. The results of the long-term investigations of very high energy extensive air showers with the calibration telescope system of the NEVOD experimental complex are presented. The top plane of the setup is used to register the electron EAS component in the primary particle energy range of $10^{14}$–$10^{15}$ eV, while the bottom plane can register muon component in the primary energy range of $10^{16}$–$10^{18}$ eV. Two independent reconstruction methods of the charged particle local density spectrum are considered. The effects of building construction and water pool on the measurement results were calculated using Geant4. The exponents of charged particles local density spectra are obtained for different energy ranges, and the presence of the second “knee” in the spectrum of the EAS muon component is confirmed. The results are compared with CORSIKA-based calculations and data from other setups.

1. Introduction

For a long time, most of EAS studies were carried out by means of the electron component. Well known form of the primary cosmic ray (PCR) energy spectrum [1] is a result of interpretation of such investigations. But the interval of $10^{14}$–$10^{15}$ eV remains poorly studied by EAS setups and there are problems in the understanding of the nature of the second “knee” at energy about $10^{17}$ eV.

Nowadays the investigations of various EAS components are attracting more attention. The calibration telescope system (CTS) [2] is a part of the Experimental complex NEVOD [2, 3] and is used for calibration of PMTs of Cherenkov water detector (CWD) by means of direct Cherenkov light from muon tracks. This setup can measure simultaneously electron and muon EAS components. Unlike big EAS arrays, the investigation method with CTS is based on the measurements of local charged particle density of EAS at the observation point [2]. CTS can register the electron EAS component in primary energy range $10^{14}$–$10^{15}$ eV and the muon EAS component in energy range $10^{16}$–$10^{18}$ eV.

2. Experimental setup

The experimental complex NEVOD is located in the MEPhI campus in a special building. The basis of the experimental complex is the CWD NEVOD which is surrounded from its three sides by the supermodules of the coordinate-tracking detector DECOR [4]. The calibration telescope system consists of two parallel planes with an area of $8 \times 10 \text{ m}^2$ which are located on the cover and on the bottom of CWD water pool. The 40 scintillation counters with size of $40 \times 20 \times 2 \text{ cm}^3$ are arranged in a chess order (figure 1) in each plane. The signals from the counters are transferred to the data...
acquisition system by means of coaxial cables. The trigger conditions for recording events in the CTS are the hits within 75 ns time gate of more than two counters (T1) in the top plane, not less than two counters (T2) in the bottom plane, and any number of counters simultaneously in both planes (T3). T1 and T2 triggers are used to register electron and muon EAS components, respectively, while T3 is used to record single muon events for calibration purposes. An example of the multiparticle event registered in the experimental complex is shown in figure 2.

We can assume that the density of charged particles is constant within the area of the CTS planes since their sizes are much less than transverse size of EAS electron component for top plane and muon component for the bottom one. Thereby, our investigation method is based on the phenomenology of the local density of charged particles [2].

We can recover the local electron density spectra (LEDS) from CTS top plane data by two different methods. The first one is based on the distribution of events in hit counter multiplicity, and the second is based on the amplitudes of the counter responses.

The CTS bottom plane data is used for recovering local muon density spectra (LMDS) from the distribution of events in hit counter multiplicity only. We do not use the events with two hit counters to recover LMDS since the calculated rate of such events tends to infinity. Unfortunately, we cannot use amplitude method of reconstruction because there is an influence of the local electromagnetic showers in water on the signal amplitudes, which cannot be correctly converted in number of muons.

3. The effects of building construction and water pool

As mentioned above, CTS is located inside the building, and additionally its bottom plane is under the 8.6 m layer of water. For estimating the effects of building construction and water pool on the measurement results we constructed a model of the experimental complex using Geant4 [5] program. EAS simulation was carried out using the CORSIKA code [6]. A piecewise power function with the “knee” at 4 PeV energy was used as a model of the PCR energy spectrum. According to calculations, the presence of the building and water leads to a systematic shift in the local density of charged particles. The calculation results depend on the method of spectrum reconstruction. For the top plane, we obtained factors of ~1.4 and ~1.9 of the local density increase with the presence of the building for spectrum reconstruction from distribution of hit counter multiplicity and from amplitudes of counter responses respectively. For the bottom plane, the factor for spectrum reconstruction from distribution of hit counter multiplicity is near to 1.3.
4. Experimental results

The experiment on electron and muon EAS components registration with the CTS was conducted from June 2013 to September 2016. Some periods of time were excluded from data analysis (separately for top and bottom planes) if problems with equipment occurred. As a result of long-term measurements, the distributions of hit counter multiplicity were obtained (see figure 3) for T1 and T2 triggers. They are used for reconstruction of local charged particle density spectra. Amplitudes of hit counter responses were converted to the number of charge particles using calibration data from events provided by T3 trigger.

![Figure 3. Distributions of hit counter multiplicity for T1 (squares) and T2 triggers (circles). Straight lines are the power law fits.](image)

4.1. LEDS reconstruction

While we are working with the CTS top plane, it is possible to compare the measurement results obtained in different ways. Reconstruction of the local electron density spectra (figure 4) was carried out from the amplitude data and from hit counter multiplicity distribution. The total live time of measurements with the top CTS plane is ~ 19.7 thousand hours. During this period, about 51.6 million events were registered with T1 trigger. The effective angle for the EAS electron component registration in the top plane is about 20° if we assume the angular distribution \( \propto \cos^{8.5} \theta \) measured with various setups near sea level. The spectrum recovered from counter response amplitudes has a clear deformation on the left side related with a threshold effect. After correction for the effect of building construction, two spectra in the figure 4 are close to each other in density range from 4 to 40 m\(^{-2}\). The exponents of LEDS were obtained by power law fitting of the experimental data (see table 1) in this density range. The value of the exponents of the spectra obtained from the CTS experimental data are in a reasonable agreement with the results of other setups operated near the sea level [7]. Also the figure 4 shows the calculated LEDS for the primary protons and iron nuclei for comparison. In simulations, power law primary spectrum with differential spectrum index \((\gamma+1) = 2.7\) was assumed. The measured spectrum is between the calculated ones for local electron density more than 2 m\(^{-2}\).

4.2. LMDS reconstruction

Bottom CTS plane location provides investigation of EAS muon component. Water layer serves as a filter for electron component and thus mainly muons can reach a depth of about 9 meters. The effect of the hadron EAS component and electromagnetic cascades produced in water on the density estimation was calculated by means of Geant4 (see section 3).

About 161.4 thousand events were registered in the bottom plane with hit counter multiplicities not less than three during about 17.1 thousand hours of the total live time measurements. The effective angle for muon bundles registered in the bottom plane is about 29° according to the angular distribution \( \propto \cos^{4.5} \theta \) measured with detector DECOR [8]. The result of the local muon density spectrum reconstruction from distribution of hit counter multiplicity is shown in figure 5. The exponents for different parts of LMDS (see table 2) were obtained by fitting the experimental data in the intervals corresponding to the two energy ranges of primary particles: \(10^{16} - 10^{17}\) eV and more.
than $10^{17}$ eV. The spectrum has a well-marked “knee” where the exponent $\beta$ changes its value: $\Delta \beta = 0.35 \pm 0.11$ ($3.2\sigma$).

Figure 4. Differential local electron density spectra reconstructed from distribution of hit counter multiplicity (circles) and from amplitudes of hit counter responses (triangles). Dotted and dashed curves are results of calculations for primary protons and iron nuclei, respectively. The arrows at the bottom of the figure point to the characteristic values of primary energy.

Table 1. LEDS exponent estimates.

| Method         | Exponent | Range (eV)     |
|----------------|----------|----------------|
| by multiplicity| 1.49 ± 0.01 | $10^{14} - 10^{15}$ |
| by amplitude   | 1.55 ± 0.01 | $3 \times 10^{14} - 2 \times 10^{15}$ |

Figure 5. Differential local muon density spectrum reconstructed from distribution of hit counter multiplicity in CTS bottom plane. Straight lines are power law fits in two ranges of primary energies.

Table 2. LMDS exponent estimates.

| Range (eV) | Exponent |
|------------|----------|
| $10^{16} - 10^{17}$ | 2.06 ± 0.01 |
| $>10^{17}$    | 2.41 ± 0.11 |

Firstly, the second knee for EAS muon component was found with DECOR detector at the same energy ($\sim 10^{17}$ eV) for zenith angles more than 60° [9]. For comparison with DECOR data, we present experimental results for DECOR at zenith angle of 35°, CTS data extrapolated to the same zenith angle, and calculated LMDS for primary protons and iron nuclei in figure 6. In calculations, primary spectrum with a knee at 4 PeV was assumed. The results obtained with CTS and DECOR are in a good agreement in an overlapping range.
Figure 6. Differential LMDS restored from DECOR data (squares) for zenith angle 35°, and CTS data (circles) extrapolated to the zenith angle 35°. Dotted and dashed curves are results of calculations for primary protons and iron nuclei respectively. The arrows at the top of the figure point to the characteristic values of primary energy.

5. Conclusions
The local charged particle density method provides possibility of investigations of primary cosmic rays in a wide energy range ($10^{14} - 10^{18}$ eV) with a small size setup at the Earth surface.

The results of LMDS measurements with CTS confirms the presence of the second “knee” in EAS muon component near the primary energy $10^{17}$ eV found earlier with DECOR detector.

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References
[1] Patrignani C et al. 2016 The review of particle physics Chin. Phys. C 40 100001
[2] Amelchakov M B et al. 2015 Calibration telescope system of CWD NEVOD as a detector of electron and muon components of EAS Physics Procedia 74 449–56
[3] Kindin V V et al. 2015 Cherenkov water detector NEVOD: a new stage of development Physics Procedia 74 435–41
[4] Barbashina N S et al. 2000 A coordinate detector for studying horizontal fluxes of cosmic rays Instr. Exper. Tech. 43 743–6
[5] Agostinelli S et al. 2003 Geant4 – a simulation toolkit Nucl. Instrum. Meth. A 506 250–303.
[6] Heck D et al. 1998 A Monte Carlo code to simulate extensive air showers (Report FZKA 6019). Germany: Forschungszentrum Karlsruhe
[7] Grieder P K F 2010 Extensive air showers, high energy phenomena and astrophysical aspects Berlin Heidelberg: Springer, vol 2
[8] Bogdanov A G et al. 2010 Investigation of the properties of the flux and interaction of ultrahigh-energy cosmic rays by the method of local-muon-density spectra Phys. Atom. Nucl. 73 1852–69
[9] Bogdanov A G et al. 2008 A new approach to EAS investigations in the energy region $10^{15} - 10^{19}$ eV Nucl. Instrum. Methods A 588 189–92