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Local density spectra of electron and muon EAS components in primary energy range from 10^{14} to 10^{18} eV

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The local density spectra of charged EAS particles are measured with the calibration telescope system of the experimental complex NEVOD. The electron and muon components of EAS are recorded separately in different ranges of the primary cosmic ray particles. The results are compared with the calculated ones.

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1. Introduction

The present picture of high-energy cosmic ray (CR) spectrum and mass composition is formed due to results of direct and indirect investigations. The direct measurements are carried out in the balloon- or space-based experiments. The maximum energy is limited to ~10^{14} eV for these investigations because of drastically decreasing particle flux. The indirect measurement technique is based on the registration of the secondary particles which are generated by CR in the Earth's atmosphere. Usually, these setups consist of the detector system which is spread over the area about 1 km^2 or more and located at the altitude from 0 to ~5000 m. The energy range from 10^{14} eV can be studied with such installations.

The energy interval from 10^{13} to 10^{15} eV is a transitional range between two ways of registration. Experimental data, obtained by various setups within this range, are scarce and often contradict each other.

A two-plane scintillation counter system was earlier developed for Cherenkov water detector (CWD) calibrating in the experimental complex NEVOD [1, 2, 3]. Small size and dense arrangement of counters provide the measurements of the local density spectrum of charged EAS particles at the Earth's surface in the energy range from 10^{14} to 10^{15} eV. Additionally, the water layer (8.6 m) between two planes makes it possible to measure the local muon density spectrum in the primary energy range from ~10^{16} to ~10^{18} eV.

2. Experimental setup

The calibration telescope system (CTS) is a part of the experimental complex NEVOD [1, 2, 3] (MEPhI, Moscow). CTS consists of two planes. In each one, there are 40 scintillation counters. CWD is located between CTS planes as shown in Figure 1. In both planes, the counters are arranged in a chess order on the 8×10 m^2 area. The distance from the bottom to the top plane is 9.45 m. The coordinate-tracking detector DECOR [3] surrounds the CWD water tank (see Figure 1) from three sides.

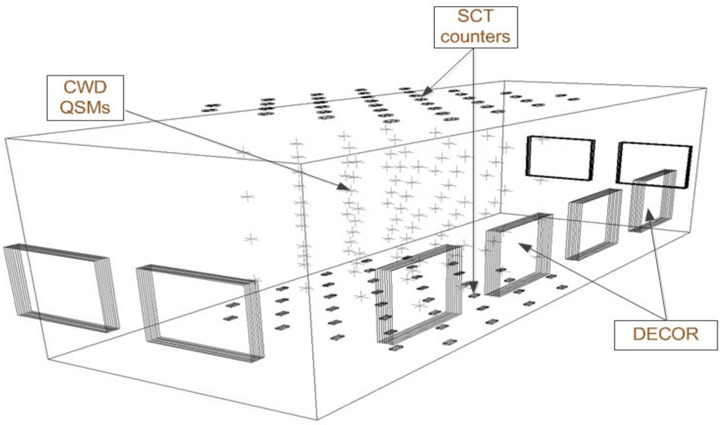

Figure 1: The experimental complex NEVOD.

The CTS scintillation counter (Figure 2) with the size 40×20×2 cm^3 is assembled from eight IHEP_SC-301 [4] scintillation plates (20×20×0.5 cm^3). Eight Kuraray Y11 WLS fibers are used to collect light to the PMT (FEU-85). The electronic board on the PMT socket serves to both PMT power supply and PMT anode signal amplifier. The Cockcroft-Walton generator [5] mounted on the board provides converting low voltage +12 V to the high one for PMT power supply. The signal from the counter and power supply are transmitted via two coaxial cables.

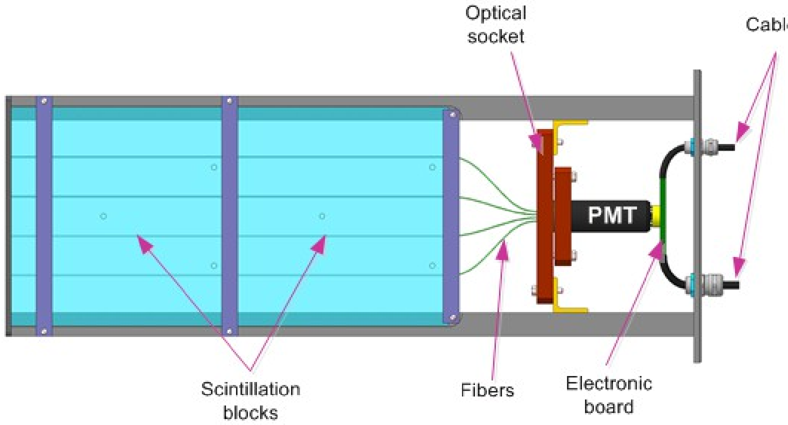

Figure 2: Interior of the scintillation counter.

Each CTS channel has been adjusted for registration up to ~60 relativistic particles. As one particle, we accept the counter response which corresponds to the energy loss of minimal ionizing particle (MIP) in 2 cm of scintillator.

3. Method of reconstruction of local density spectrum

The application of the technique of local density spectrum measuring [6] is possible if the setup has a small size compared to EAS transverse size. Assuming that the particle density is equal for each counter in a plane, we can evaluate the counter hit probability p as:

$$p = 1 - \exp(-S_{\text{eff}} D) \quad , \tag{1}$$

where S_{eff} is the effective counter area and D is the particle density. The effective counter area depends on the particle incidence angle (θ) and a counter efficiency (η=0.95):

$$S_{\text{eff}} = \eta S \cos\theta \quad . \tag{2}$$

According to earlier results [7], the integral spectrum of events has approximately a power law dependence on the particle density with an exponent β, :

$$F_0(D) \sim D^{-\beta} \quad . \tag{3}$$

Therefore, for calculating we used a trial spectrum of local density of charged EAS particles in the following form:

$$\frac{dF_0}{dD\,d\Omega} = A_0 (D/D_0)^{-(\beta+1)} f(\theta) \quad , \tag{4}$$

where A_0 is the normalization factor, the constant D_0 = 1 m^{-2} is used for dimension compensation only, and $f(\theta)$ is EAS angular distribution function. For the electron component of EAS [7]:

$$f(\theta) = \exp\left(-\beta X_0 (\sec\theta - 1)/\Lambda\right) \quad , \tag{5}$$

where X_0 is an atmospheric depth (~1020 g/cm^2), Λ is a nucleon attenuation length in the atmosphere (~120 g/cm^2). For the muon EAS component (according to the experimental data from DECOR [8]):

$$f(\theta) = \cos^{4.5}\theta \quad . \tag{6}$$

Expected value of the counting rate for a fixed multiplicity *m* is a double integral of product of the probability of *m* hit counters with the trial spectrum over the density and solid angle:

$$\nu_m = 2\pi \int_0^{\infty} \left(\int_0^1 C_n^m p^m (1-p)^n \frac{dF_0}{dD d\Omega} d\cos\theta \right) dD \quad , \tag{7}$$

where *m* is a coincidence multiplicity, *n* is the total number of counters in a plane, and *p* is a counter hit probability (1).

Exponent value β is selected on the basis of the analysis of the ratio of experimental counting rates to calculated ones. If a real local density spectrum has a power law, ratio of the counting rates will be close to constant in the analyzed range of multiplicity for correctly chosen value of the exponent.

The density dependences of the integrand in formula (7) for vertical EAS axis direction are shown in Figure 3 separately for electron and muon components. The selected trial spectrum exponent values are 1.5 and 2.0 respectively.

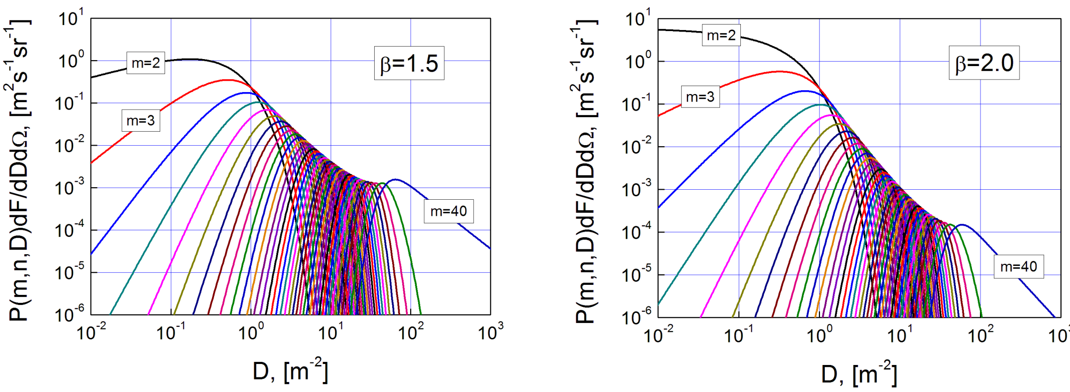

Figure 3: The density dependences of the integrand in formula (7) for various multiplicities of hit counters: for the electron component (left), for the muon component (right).

In the multiplicity range from 5 to 39, the distributions in Figure 3 are rather narrow; it can be seen that for the muon component the integral in formula (7) is divergent for $m = 2$.

Due to a steep shape of the local density spectrum, the values of the mean logarithmic density D' have been assigned to each combination of zenith angle θ and multiplicity *m* (from 3 to 40). Thus, for the reconstruction of the local density spectrum from the distribution of multiplicities of hit counters we have the equation:

$$\frac{dF_0}{dD d\Omega} = \frac{\nu_m^{ex}}{\nu_m} (D_m' / D_0)^{-(\beta+1)} f(\theta) \quad . \tag{8}$$

As a normalization factor in formula (8), the ratio of experimental counting rates to the expected ones is used.

4. Results of measurements

4.1 The local density spectrum of charged particles

Electron component of EAS constitutes the main part of charged EAS particles on the Earth surface at CR energy ~10^{14} eV. The transverse size of the EAS electron component is determined by the Moliere radius (~70 m at sea level). It is much more than the CTS plane area (80 m^2). Thus, the basic condition for measuring of the local density spectrum of charged EAS particles is satisfied.

Triggering condition for the CTS top plane was the coincidence of no less than three hit counters in the time gate of 75 ns. In total, about 31.5 million events were registered at the "live time" of 11806 h (~492 days). The results of measurements of the local density spectrum of charged EAS particles are shown in the Figure 4. The spectrum is reduced to the zenith angle which corresponds to the mean logarithmic value of cosθ (~20°). The calculated spectra of the local electron densities for primary protons and iron nuclei are also shown for comparison.

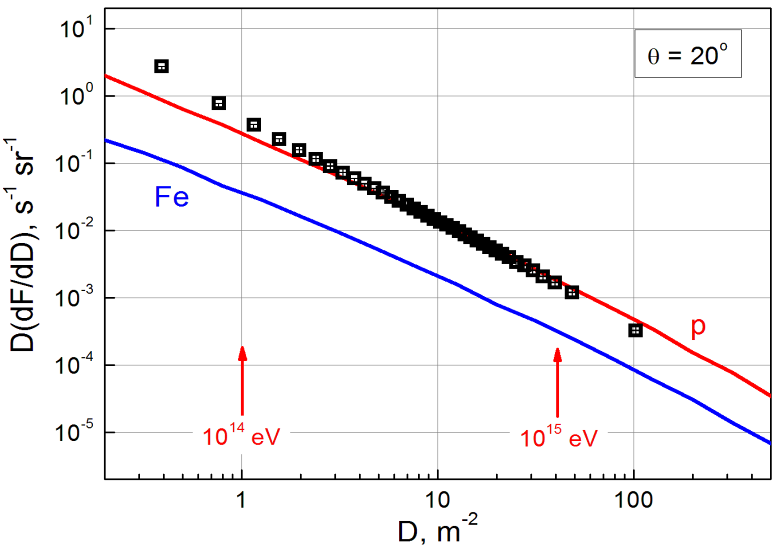

Figure 4: Local density spectra of charged EAS particles. Squares: the spectrum reconstructed from counter multiplicity, red curve is the calculated spectrum for primary protons, blue curve is the calculated spectrum for primary iron nuclei. The mean logarithmic primary proton energies are marked by arrows.

To calculate the spectrum of the local density of the charged EAS particles, we used the average lateral distribution functions (LDF) of particles, obtained by simulating showers with the CORSIKA v.7.40 program [9]. A combination of SIBYLL2.1 and FLUKA2011 was used as the model of hadron interaction, and the EGS subroutine was used to calculate the EAS electron component. The threshold energies of the secondary particles were 100 MeV for hadrons and muons and 1 MeV for electrons. Showers were sampled for a fixed set of energies for the primary particles of cosmic rays (protons and iron nuclei) in the range of 10^3 to 3×10^7 GeV. The spectrum of primary cosmic ray particles was chosen in the form of:

$$\frac{dN}{dE}=\begin{cases}5.0\cdot10^4\cdot(E\,,\mathrm{GeV})^{-2.7}\,, E<E_{\mathrm{knee}}\\ 5.0\cdot10^4\cdot(E\,,\mathrm{GeV})^{-2.7}(E/E_{\mathrm{knee}})^{-0.4}\,, E\geq E_{\mathrm{knee}}\end{cases}, \tag{9}$$

where $E_{\mathrm{knee}} = 3\times10^6$ GeV.

4.2 The local muon density spectrum

There is no possibility to measure the local density spectrum of EAS electron component in the bottom CTS plane since the value of the Moliere radius in water is about ~9 cm. At the same time, the water layer with 8.6 m height provides possibility to select the muon EAS component. We can measure the local muon density spectrum as far as the EAS transverse size for the muon component reaches several kilometers.

Triggering condition for the bottom plane was the coincidence of no less than two hit counters in the time gate of 75 ns. However, we excluded 2-fold events from the data analysis since they included a significant admixture of random coincidences, and in the formula (7) the integral over density diverges for m=2. About 113 thousand events with $m \geq 3$ were registered at the "live time" of about 11909 h (~496 days). The event rate at high multiplicities is very low (a few per year), therefore we have combined several neighboring values of multiplicity. The results of measurements of the local muon density spectrum are shown in Figure 5 for the zenith angle which corresponds to the mean logarithmic value of cosθ (~29°). The colored solid lines on the plot are results of fitting data in different ranges of the local muon density. The energy marks (arrows) are set in correspondence with the estimates [8] obtained earlier.

More than two orders of magnitude of the primary CR energy may be studied using CTS setup for multi-muon events detection. The result of measuring of the local muon density spectrum gives a confirmation of the existence of the second "knee" for the primary CR energy near the value of 10^{17} eV, which was first found in muon EAS component earlier [8, 10].

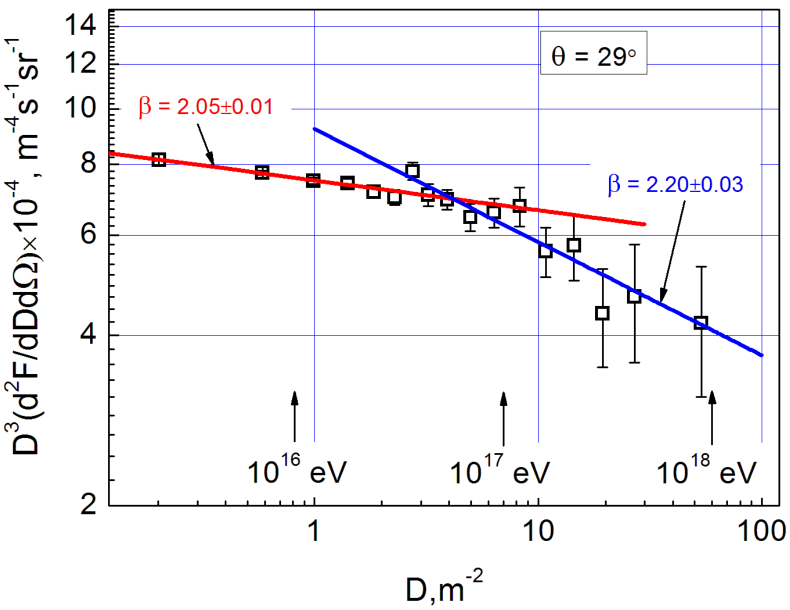

Figure 5: Local muon density spectrum at zenith angle 29°. Squares: reconstructed spectrum from the multiplicity distribution, red line is a fit in density range 0.2 – 8.3 m^{-2}, blue line is a fit in density range 2.7 – 54 m^{-2}. The mean logarithmic values of primary energy are represented by arrows.

Conclusion

The CTS setup provides the possibility for investigating EAS in the CR energy range from $\sim10^{14}$ to $\sim10^{15}$ eV due to a small size in conjunction with the measuring technique. The exponent of the local density spectrum of charged particles is close to 1.5 in the density range from 3 to 30 m^{-2}. Additionally, due to the presence of the water absorber, there is a possibility to measure the local muon density spectrum in the CR energy range from $\sim10^{16}$ to $\sim10^{18}$ eV. The exponent value is changed for the particle densities around ~4 $м^{-2}$. The second “knee” region of the CR energy spectrum is near to 10^{17} eV. The exponent estimates are 2.05 and 2.20 respectively for two parts of the local muon density spectrum (below and higher the “knee”).

Acknowledgments

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