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Experimental Complex
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The second knee observed in the local muon density spectra at various zenith angles

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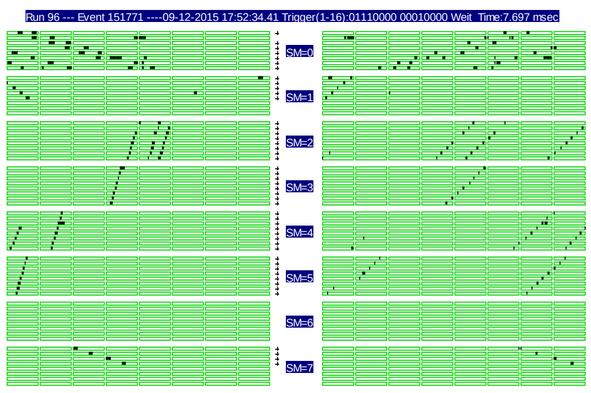
Annotation

The presence of the 2nd "knee" in the spectrum of the EAS electromagnetic component is confirmed by results of several large-scale setups. An indication of the 2nd knee existence in the spectrum of the EAS muon component was firstly obtained in 2008 on the experimental complex NEVOD. The report presents the results of long-term measurements of local muon density spectra (LMDS) at very high energies of the primary particles obtained with two setups (DECOR and CTS) which are parts of the experimental complex NEWOD (MEPhI, Moscow).

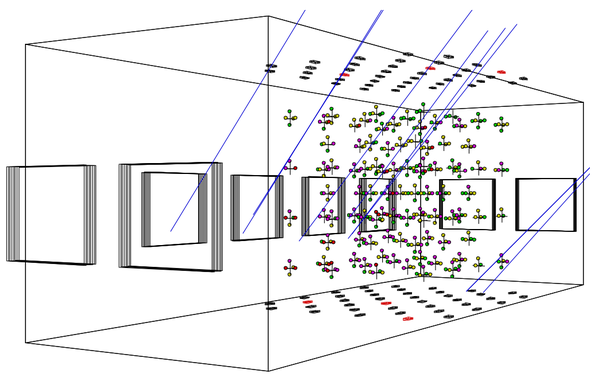
The experimental complex NEVOD

The experimental complex NEVOD is based on the water Cherenkov detector (CWD) which is located at the Earth surface. It includes coordinate detector DECOR and CWD calibration telescope system (CTS) which provide investigations of the muon EAS component in a wide energy range of primary particles (10^{15} – 10^{18} eV).

Eight DECOR supermodules are arranged around the CWD water pool. Each supermodule consists of eight vertical planes (8.4 m^2) of streamer tubes. The angular accuracy for reconstructed muon tracks is better than 0.8°.



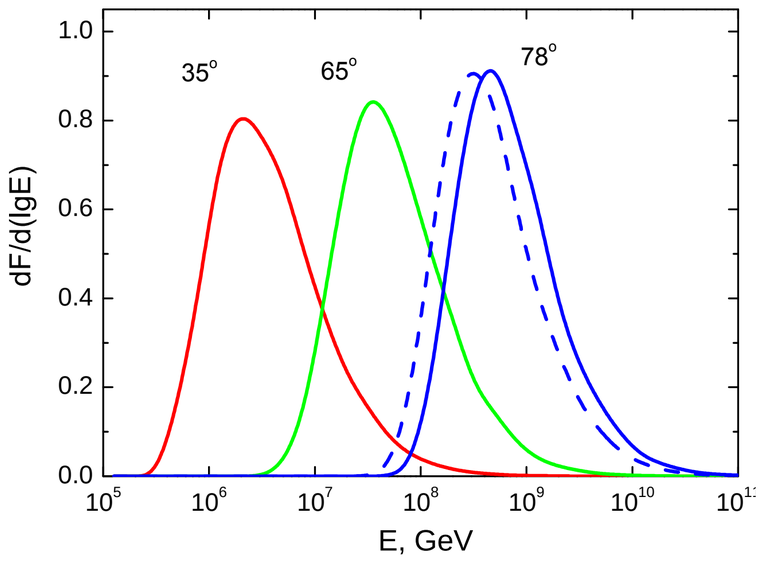
The DECOR response on the muon bundle passage.



The geometric reconstruction of the event with the muon bundle in the experimental complex NEVOD.

Registration of muon bundles at large zenith angles

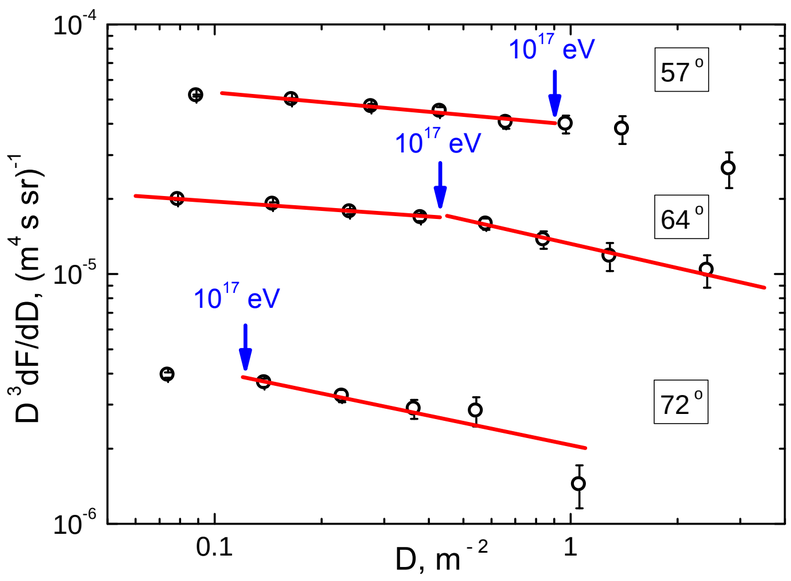
The experiment of muon bundle registration was performed in two periods: 2002 – 2007 and 2012 – 2016. The first result was published in 2008. The generalized results for the entire period of measurements are presented in this work.



According to the estimates, the same local muon density corresponds to different distributions of the energy of the primary particles registered at different zenith angles. By increasing the zenith angle of muon bundle observation, we can explore the higher energy of the primary particles.

Energy distributions of primary particles contributing to events with fixed muon density for different zenith angles. Solid and dashed curves are results of calculations for primary protons and iron nuclei, respectively.

Differential LMDS for DECOR detector were restored from distributions of muon bundle multiplicities, which were recorded in different zenith-angular ranges: 55°–60°, 60°–69°, 69°–75°. More than 39 thousand events with muon number more than 5 were collected. The effective values of zenith angles in these bands are 57°, 64° and 72°. The exponents (β) of LMDS are 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.

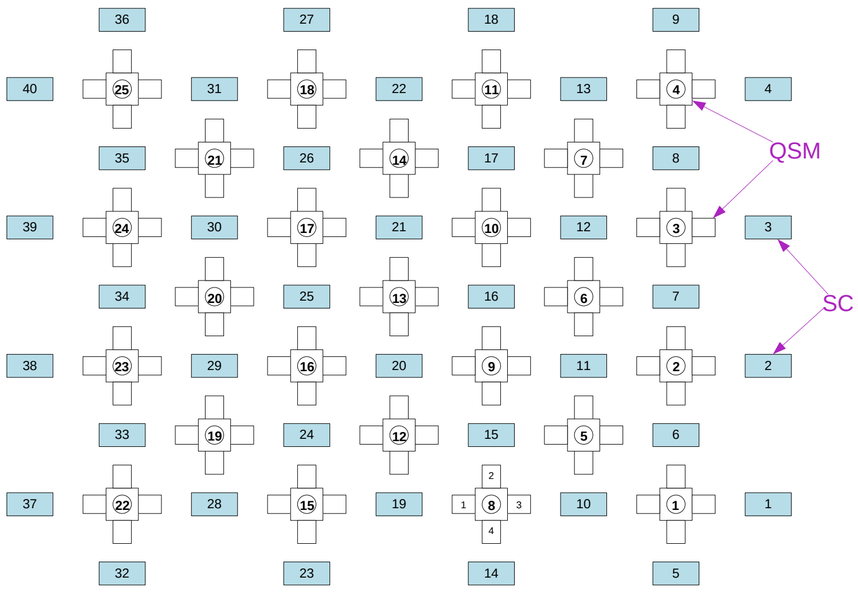


Differential LMDS for three values of zenith angles: 57°, 64° and 72°.

Zenith angle	$E_0 = 10^{16} – 10^{17}$ eV	$E_0 > 10^{17}$ eV
57°	2.129±0.027	-
64°	2.099±0.016	2.323±0.103
72°	-	2.296±0.064
Weighted average	2.107±0.014	2.303±0.054

Registration of muon bundles near the vertical direction

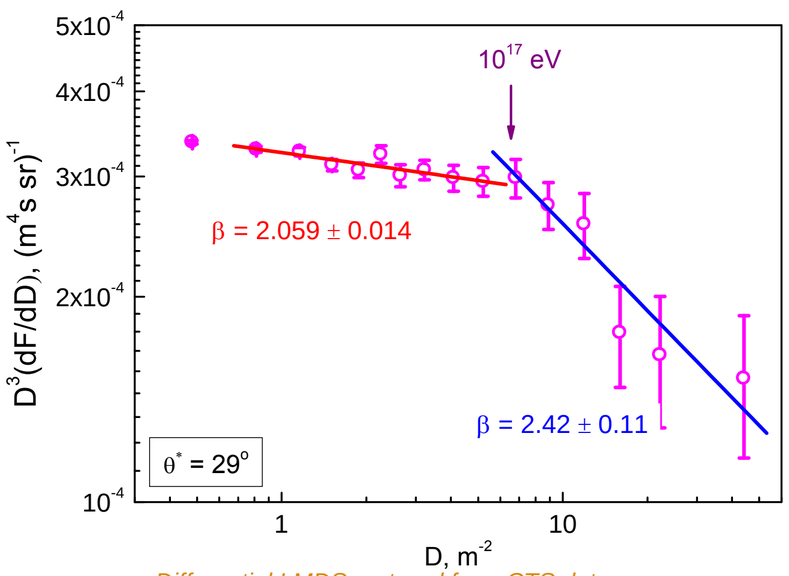
The experiment of muon bundle registration with the CTS was performed from 2013 to 2016. Events were recorded when there were at least 3 hit counters in the plane. Full live time was ~17300 hours (~164000 events). The first result was published in 2015.



CTS consists of two planes of scintillation counters. In each plane 40 counters (40×20×2 cm^3) are arranged in a chess order on the area of 8×10 m^2.The top and bottom planes are located above and under the CWD water pool, respectively. Thereby, the 8.6 m water shield protects the bottom plane from the EAS electromagnetic component.

CWD top view with vertical strings of quasispherical modules (QSM) and CTS plane with scintillation counters (SC).

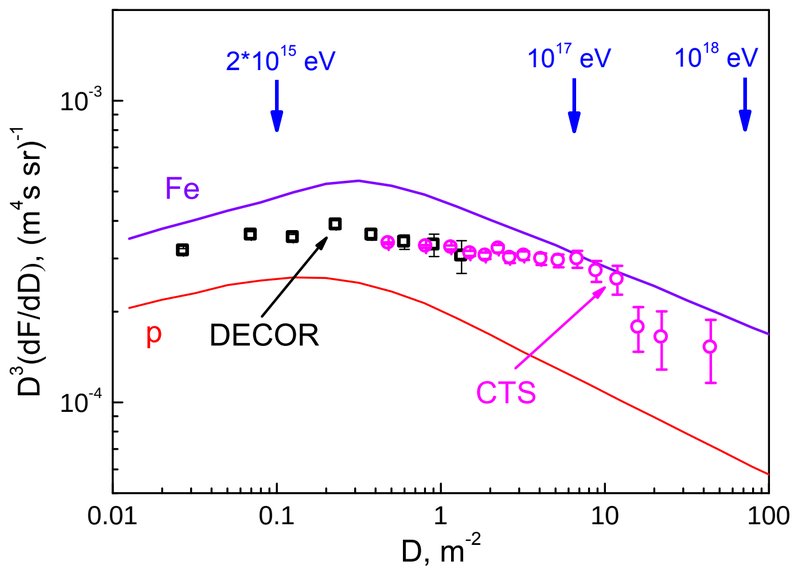
Differential LMDS for the CTS bottom plane were restored from hit counters multiplicity distribution. The effective angle of muon bundle registration is 29°. As for DECOR, the exponents of LMDS were obtained by fitting the experimental data in the intervals corresponding to the two energy ranges of primary particles: 10^{16} – 10^{17} eV and more than 10^{17} eV.



Differential LMDS restored from CTS data.

Comparison of measurement results

Differential LMDS obtained with DECOR and CTS were compared for close values of the zenith angles. For DECOR we used the zenith angels range from 30° to 40°; CTS data were extrapolated to the zenith angles of 35°.



Differential LMDS restored from DECOR data for zenith angle 35° and CTS data extrapolated to the zenith angle 35°. Solid colored curves are results of calculations for primary protons and iron nuclei. The arrows at the top of the figure point to the characteristic values of primary energy. As a model of the cosmic ray energy spectrum, a piecewise power function with the "knee" at 4 PeV energy was used.

We obtained the spectrum exponent variation near the energy 10^{17} eV of primary particles:

DECOR: $\Delta\beta = 0.196 \pm 0.056 \ (3.5\sigma)$

CTS: $\Delta\beta = 0.36 \pm 0.11 \ (3.3\sigma)$

Conclusion

The LMDS method provides investigation of primary cosmic rays in a wide energy range (10^{15} – 10^{18} eV) with small size setups at the Earth surface.

The results of LMDS measurements with two setups of the experimental complex NEVOD showed the increasing of the spectrum exponent value ($\Delta\beta$~ 0.2 – 0.3) near the primary energy ~10^{17} eV.

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