Energy deposit of muon bundles detected at various zenith angles in the Cherenkov water calorimeter


National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute), Moscow, Russia

Osservatorio Astrofisico di Torino – INAF, Torino, Italy

Dipartimento di Fisica dell’ Universita di Torino, Italy

E-mail: RPKokoulin@mephi.ru
Excess of muons in EAS at ultra-high energies: (‘muon problem’, or ‘muon puzzle’)

Pierre Auger Observatory (ICRC-2011, Beijing)

DECOR Collaboration (ISVHECRI-2008, Paris)
Problem of muon excess and energy deposit measurements

In several UHE experiments (DELPHI, ALEPH, DECOR, PAO,...), excess of muons in comparison with calculations is observed. Measurements of the muon component energy characteristics are required. Possible approach: study of muon bundle energy deposit.

Muon energy loss: \( \frac{dE}{dx} = a + bE \). If some excess of high-energy muons appears, it should be reflected in the dependence of the energy deposit on the primary particle energy.

An experiment on investigation of the energy deposit of inclined muon bundles at NEVOD-DECOR complex started in 2012. Here, results of the analysis of the data accumulated in May 2012 – February 2017 are presented.
NEVOD-DECOR experimental complex

**NEVOD**
9 x 9 x 26 m³ volume;
91 QSM; 546 PMT

**DECOR**
8-layer supermodules (SM) of streamer tubes.
Accuracy about 1 cm and better than 1°.
Response of DECOR coordinate-tracking detector for a muon bundle event

SM=0
SM=1
SM=2
SM=3
SM=4
SM=5
SM=6
SM=7

SM5: X-view, Y-view
Local muon density in the event and EAS arrival direction are estimated from DECOR data, whereas the energy deposit is measured in the Cherenkov water calorimeter NEVOD.
Contribution of various primary energies to formation of muon bundle events at different zenith angles (simulation)

Simultaneous registration of muon bundles in a wide interval of zenith angles and muon multiplicities ensures covering a very wide range of primary energies in frame of a single experiment.
Experimental data: statistics

Three series of measurements:

03.05.2012 – 20.03.2013, 5542 ч
16.07.2013 – 08.04.2015, 11898 ч
16.07.2015 – 28.02.2017, 11735 h (is continuing)

**Total**: 29175 hours ‘live’ observation time

Results of muon bundle selection:

\( m \geq 5, \ \theta \geq 55^\circ, \ \text{two 60}^\circ\text{-wide sectors in } \phi \) – 49460 events

Additionally (for 3253 h): \( 40^\circ \leq \theta < 55^\circ \), – 15084 events

As a measure of the CVD response, sum of all PMT signals of the NEVOD is used (\( \Sigma \), in photoelectrons, ph.e.).

Unbiased estimate of local muon density in the event calculated as

\[ D = \frac{(m - \beta)}{S_{\text{det}}(\theta, \phi)} ; \]

here \( m \) is the number of muons, \( \beta \approx 2.1 \) is the LMDS slope.
Correlations of the total energy deposit with the local muon density

In a first approximation, total energy deposit is proportional to muon density in the event (line in the figure). Therefore, further we consider the specific energy deposit $\Sigma N(\text{ph.e.}) / D$, that is CWD response normalized to the muon density.
Dependence of the muon bundle average specific energy deposit on zenith angle

At $\theta \geq 55^\circ$, practically pure muons remain. The increase of the energy deposit with zenith angle reflects the increase of the average muon energy in the bundles (up to 500 GeV near 85°). A reasonable agreement with simulations, except the region between 65 – 75° ($10^{17} \sim 10^{18}$ eV).
Dependence of the average specific energy deposit on muon density for different zenith angles

NB! For a fixed zenith angle interval, this is a direct test of the dependence of $<\Sigma/D>$ on the energy of primary particles.

Simulations reveal a tendency to a slow decrease of muon energy in the bundles with the increase of primary energy. In contrast, data indicate some increase of the average specific energy deposit at high muon densities (corresponding to effective primary energies more than $10^{17}$ eV).
Conclusion

An experiment on the measurements of the energy deposit of muon bundles in inclined EAS is being conducted at the NEVOD-DECOR complex. For the moment, preliminary analysis of data accumulated for 29.2 thousand hours of observations has been performed.

An appreciable dependence of the average specific energy deposit (normalized to the muon density) on the zenith angle has been revealed. This dependence is in a good agreement with CORSIKA-based simulations.

An indication for an increase of the energy deposit in comparison with expectation at primary energies higher than $10^{17}$ eV has been found. However, a further increase of statistics and a careful analysis of possible systematic effects are necessary.

Accumulation of experimental data, their processing, simulations and data analysis are being continued.
Thank you!