Intensity of muon bundles according to the NEVOD-DECOR cosmic ray experiment

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Abstract. Data of NEVOD-DECOR experiment on investigations of inclined cosmic ray muon bundles for a long time period (May 2012 – May 2020) are presented. Their comparison with the results of calculations based on simulations of extensive air shower hadron and muon components is carried out. The analysis showed that the observed intensity of muon bundles at primary particle energies of about $10^{18}$ eV and higher can be compatible with the expectation only under the assumption of an extremely heavy mass composition of cosmic rays. On the contrary, measurements of the depth of the shower maximum in the atmosphere in the experiments using air fluorescence technique, favour a light mass composition of primary cosmic rays at these energies.

1. Introduction

Primary cosmic rays (CR), predominately protons and nuclei, carry important information about the physical processes occurring in our Galaxy and the Universe. At energies above $10^{15}$ eV, the only way to study the main properties of primary CR flux (energy spectrum and mass composition) is the registration of extensive air showers (EAS) on the surface of the Earth. EAS is nuclear electromagnetic cascade initiated by an interaction of primary CR with the atoms of the atmosphere. Thus, when interpreting EAS data, there are several unknowns, namely the spectrum, composition, and characteristics of hadronic interactions.

The EAS muon component is formed mainly as a result of the decays of pions and kaons produced in numerous interactions of hadrons in the atmosphere and is often used to obtain information on the mass composition of CR and to check hadronic interactions models. Of a particular interest are events with muon bundles which represent a simultaneous (within tens of nanoseconds) passage through the detector of several genetically related penetrating particles with almost parallel trajectories. To date, NEVOD-DECOR is the only experiment where long-term systematic studies of muon bundles in a wide range of zenith angles are carried out.
2. NEVOD-DECOR setup and experimental data

NEVOD-DECOR setup is located at MEPhI and includes Cherenkov water calorimeter NEVOD [1] with volume of 2000 m$^3$ and coordinate-tracking detector DECOR [2] with total area of 70 m$^2$. DECOR consists of 8 supermodules (SMs) which are located in the galleries of the experimental complex building on three sides around the water tank. Each SM has an effective area 8.4 m$^2$ and consists of 8 vertical planes of streamer tube chambers. The planes of the chambers are equipped with a two-dimensional system of external readout strips. Spatial and angular accuracy of muon track location in the SM is better than 1 cm and 1°, respectively.

In the present analysis the data on muon bundles accumulated over the period from May 2012 to May 2020 were used (“live” observation time is more than 50 thousand hours). About 90 thousand events with muon multiplicity $m \geq 5$ and zenith angles $\theta \geq 55^\circ$ and additionally about 30 thousand events in the range of zenith angles from 40 to 55° have been selected. In order to improve muon identification, only events in two 60°-wide sectors of azimuth angles were analysed, where most of DECOR SMs (six of eight) are screened by the water tank of the detector NEVOD. The selection procedure includes several stages: trigger level, software reconstruction and selection, final event classification and track counting by the operators. An example of the event with a muon bundle with $m = 20$ and $\theta = 59^\circ$ registered by the DECOR is shown (in two projections) in figure 1. As a whole, muon bundles have a very bright signature in the DECOR response and cannot be confused with other multi-particle events. For each event the number of tracks in the muon bundle and its direction can be obtained.

![Event with a muon bundle detected in the DECOR.](image)

3. Results of data analysis on muon bundles

For the physical analysis of the data, the previously developed method of local muon density spectra (LMDS) [3] was used. The typical dimensions of the air shower muon component (~ km) are much larger than the size of the NEVOD-DECOR setup (tens of meters), therefore the detector can be considered a point-like one. At a first approximation local muon density in the event can be estimated as $D \sim m / S_{det}$, where $m$ is muon bundle multiplicity and $S_{det}$ is DECOR area for a given direction. Distribution of events in local muon density $D$ forms the LMDS. The procedure of the reconstruction of experimental LMDS in a form independent of the detector, taking into account geometric factors, Poisson fluctuations of the number of muons hitting the detector, the efficiency of streamer tube chambers, trigger conditions and event selection conditions was described in detail in paper [3].

For correct interpretation of the experimental data, calculations of the expected LMDS based on simulation of the EAS muon component by means of CORSIKA program [4] were carried out. The building of such LMDS was carried out using two-dimensional muon lateral distributions taking into
account the Earth's magnetic field, threshold energy of particles, etc. for a set of fixed zenith angles and energies of primary protons and iron nuclei in a wide range; a detailed description of this procedure can be found in [3]. Two actual (post-LHC) hadronic interaction models here were used: QGSJET-II-04 and SIBYLL-2.3c.

Differential local muon density spectra for 9 zenith angle intervals are shown in figure 2. Experimental data of NEVOD-DECOR setup are marked by symbols. Solid and dashed curves represent the results of the CORSIKA-based calculations for SIBYLL-2.3c and QGSJET-II-04 models, respectively. In calculations, two limiting cases of the mass composition of primary CR were considered: only protons (p, lower pairs of the curves for each zenith angle) and only iron nuclei (Fe, upper pairs of the curves). As a reference model for the energy spectrum of primary CR, a piece-wise power law function for several energy ranges was applied [5].

![Figure 2. Experimental and calculated local muon density spectra for nine zenith angles.](image)

It follows from the figure that for the same local muon density, the intensity of muon bundles significantly decreases (by more than three orders of magnitude) with increasing of the average zenith angle from 42 to 82°.

For the convenience of comparing LMDS at various zenith angles, we use the z-scale, which was proposed by the Working group on Hadronic Interactions and Shower Physics [6]:

$$z = \frac{(\ln N_{\mu}^{\text{obs}} - \ln N_{\mu\text{p}}^{\text{sim}})}{(\ln N_{\mu\text{Fe}}^{\text{sim}} - \ln N_{\mu\text{p}}^{\text{sim}})},$$  

where $N_{\mu}^{\text{obs}}$ is the observed value (muon density, muon number, intensity of muon bundles, etc.), $N_{\mu\text{p}}^{\text{sim}}$ and $N_{\mu\text{Fe}}^{\text{sim}}$ are the simulated estimates of this value for EAS initiated by primary proton and iron; $z = 0$ corresponds to pure proton showers and $z = 1$ corresponds to pure iron showers.

Using the LMDS method, it is possible to estimate the effective energies of primary particles $E_0$ according to the NEVOD-DECOR data. The features of the method of LMDS are discussed in detail in papers [3,5]. It is important to emphasize that at the same local density, muon bundles arriving at larger zenith angles will be associated with air showers from primary particles with higher energies. For example, for local density $D \approx 0.2$, that corresponds to about 5-7 muons hitting the DECOR SMs, the energies of primary protons, giving the main contribution to the selected muon bundles with zenith angles of 42 and 82°, will be $E_0 \approx 5 \times 10^{15}$ and $2 \times 10^{18}$ eV, respectively (the difference reaches several orders of magnitude). This is due to the fact that with the increase of zenith angle, muons travel a
longer path in the atmosphere and are influenced by the Earth's magnetic field. As a result the lateral spread of muons in bundles increases. Muon bundles are detected at different distances from the EAS axis, and the event collection area in this case is determined by the cross section of the EAS muon component (~ several km²) instead of the detector size (~ tens of square meters). This allows us to obtain statistically significant results at the energies of primary particles ~ 10^{18} eV.

Combining the local muon density spectra obtained on the NEVOD-DECOR setup at different zenith angles by means of z-scale for the model of high-energy hadronic interactions QGSJET-II-04 is shown in figure 3. As one can see, the data obtained in different intervals of zenith angles overlap and are in good agreement with each other. It can be seen from the figure that at the energies ~ 10^{16} eV experimental points are close to the results of the calculations for a light mass composition of primary CR. At higher energies relative increase of muon bundle intensity may be interpreted as a trend to a heavier mass composition. But at the energy ~ of 10^{18} eV, NEVOD-DECOR data and calculations are compatible only under the assumption of an extremely heavy mass composition (iron nuclei). This conclusion is consistent with our previous data and is confirmed by data on multi-muon events obtained in a number of other experiments, see e.g. review [6].

Figure 3. Comparison of the NEVOD-DECOR data for different zenith angles in terms of z-scale.

On the contrary, measurements of the depth of the shower maximum $X_{\text{max}}$ in the atmosphere in the experiments using air fluorescence technique (Pierre Auger Observatory [7], Telescope Array [8], HiRes [9]), favour a light (predominantly proton) mass composition of primary CR at the energies about 10^{18} eV.

This problem in the study of cosmic rays has been called the “muon puzzle” [10]. One of the possible ways to solve it is to measure the energy characteristics of the muon component of an EAS. Such an experiment is currently being conducted at the NEVOD-DECOR setup [11]. The deployment of the new detector TREK based on drift chambers with larger area and better two-track resolution in the complex NEVOD will allow us to expand the energy range [12].

4. Conclusion

The experiment on the long-term systematic investigations of inclined muon bundles formed as a result of interactions of primary cosmic ray particles with energies 10^{16} – 10^{18} eV is being conducted at the NEVOD-DECOR setup. Accumulation of experimental data and their analysis are being continued.
The present data on intensity of muon bundles observed in the NEVOD-DECOR experiment at the energies of primary cosmic rays about $10^{18}$ eV and higher requires the assumption of an extremely heavy (iron nuclei) mass composition. This result is consistent with data of several experiments investigating the muon component of air showers at very high energies. However, such an assumption is in a strong contradiction with the results of $X_{\text{max}}$ measurements of electromagnetic component of the EAS in the specified energy range. Unlikely such a contradiction can be resolved without serious changes of the existing hadronic interaction models.

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