Spatial distribution of Cherenkov light from cascade showers in water

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Abstract. The analysis of spatial distribution of Cherenkov light generated by cascade showers in Cherenkov water detector (CWD) NEVOD was performed. Showers generated by nearly horizontal muons were selected. Muons tracks were reconstructed with high precision using the coordinate tracking detector DECOR. For the first time, the dependence of Cherenkov light intensity on the depth of a shower at different distances from its axis was measured.

1. Introduction

Cherenkov water detectors are the most widely developing instruments for research of the characteristics of cosmic rays, for studies of muons and neutrinos with extremely high energies. The energy of these particles is estimated through cascade showers. The topical experimental task is to investigate the distribution of the Cherenkov light from cascade showers in water. Its decision will allow to refine approaches to selection of cascades and reconstruction of their parameters, and possibly also to improve the models of high energy cascade development which are implemented in scientific software packages. So far this problem has not been studied experimentally. The operating large-scale Cherenkov detectors such as Baikal, ANTARES, IceCube, have the distances between the measuring modules that exceed several times the longitudinal size of the shower in water. It limits the possibility to obtain the detailed picture of the Cherenkov light generated by the cascade.

In the present work the light field from the cascade showers was studied at the Unique Scientific Facility 'Experimental complex NEVOD' [1] located in National Research Nuclear University MEPhI. The Cherenkov detector, which is a part of the complex NEVOD, has the dense spatial lattice of detecting modules. This enables to obtain the distribution of Cherenkov light with the step of detalization about 0.5 m, which is determined by the size of the detecting modules.

The water reservoir of the CWD NEVOD has the size $9 \times 9 \times 26$ m^3. The detecting system is a spatial lattice with quasi-spherical modules (QSMs) at its nodes that register the Cherenkov radiation from relativistic charged particles (the total number of QSMs in the lattice is 91). Each QSM consists of six FEU-200 photomultipliers with flat photocathodes oriented along the orthogonal coordinate system axes.

The small step of the spatial lattice (2.5 m along the detector, 2 m across it, and 2 m in depth) and the wide dynamic range of the registered signals (1–10^5 photoelectrons for each photomultiplier [2]) allow cascade showers to be investigated by measuring the full cascade curve in individual events.

2. Selection of cascade showers

The events with cascades generated in the water reservoir of the CWD NEVOD by the nearly horizontal muons were studied. Tracks of muons were reconstructed using the coordinate-tracking detector DECOR [3]. Each track was registered by the pair of supermodules located at the opposite short sides of the reservoir. Such a way the registered muons have a narrow range of zenith (85–90 degrees) and azimuthal (±15 degrees from the longitudinal CWD axis) angles. The mean energy of such muons is about 100 GeV.

The problem of reconstructing the cascade curve for showers with a known axis position was solved in [4]. The reconstruction of experimental cascade curves is based on recalculating the responses from photomultipliers that detect the Cherenkov radiation from the shower particles (the direction of which is assumed to coincide with the track of the parent particle and with the axis of the shower) into the number of these particles. It is also assumed that the Cherenkov photons are emitted at the same angle to the axis.

The part of the axis of the shower that is inside the detecting system is divided into bins. The number of charged particles falling into each bin which can be 'seen' by PMTs of the detector is measured. The length of the bin is one radiation length that equals to 36.1 g/cm^2 for water. The energy of the shower is reconstructed by fitting the experimental dependence of number of radiating cascade particles on the depth with a function that is one-dimensional cascade curve approximation [5].

The events with showers with the reconstructed energies in the range from 100 GeV to 500 GeV were selected from the experimental series lasting 12 thousand hours of live time. The final sample size is 635 events.

3. Distribution of light from cascade showers in water

The dependence of QSM response on its distance from the axis of the shower and on the depth of the shower (measured along its axis) for the selected events is examined. The reconstructed point of the maximum of the shower t_{max} (the age of shower $s = 1$) is taken as the origin for the depth axis.

The square root of the sum of squared amplitudes of triggered PMTs is taken as the response of the module; as shown in [6], this value does not practically depend on the incident light direction for the quasi-spherical module with 6 PMTs. The responses of the modules in all events are normalized to reconstructed energy values:

$$B = \frac{\varepsilon_0}{\varepsilon} \sqrt{\sum A_i^2} \ ,$$

where ε_0 is the normalizing energy of 200 GeV (close to the average energy of showers in the sample);

ε is the reconstructed energy of the shower in event;

A_i is the amplitude of the i-th PMT in a QSM (in photoelectrons, ph.e.).

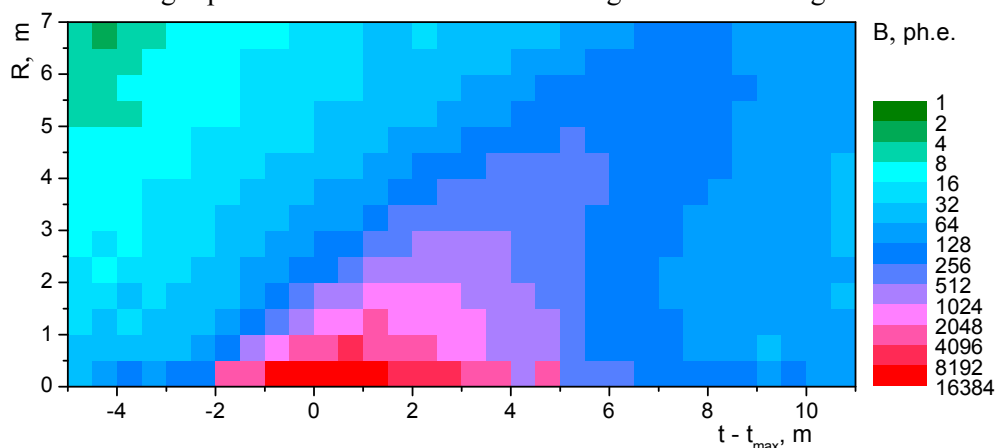The obtained average spatial distribution of Cherenkov light is shown in figure 1.

Figure 1. The dependence of Cherenkov light intensity on the depth of the shower (t-t_{max}) at different distances (R) from its axis.

The graph shows that the propagation of the light from the cascade has a good directivity; the light cone corresponding to the angle of Cherenkov radiation in water ($\theta_C \approx 41°$) is clearly visible. However, it is also evident that the light spreads not strictly under the Cherenkov angle to the axis of shower, but almost in all directions. It is mainly caused by the deviation of the cascade particles from the direction of the shower axis due to their multiple scattering. It is also necessary to take into account the light attenuation in water for a more detailed analysis.

Since the parameters of the light attenuation are the same for cascades and for single muons, it is reasonable to consider the ratio of light intensity for cascades (B) to the intensity measured for events with single muons (B_μ). The spatial distribution of this value is presented in figure 2.
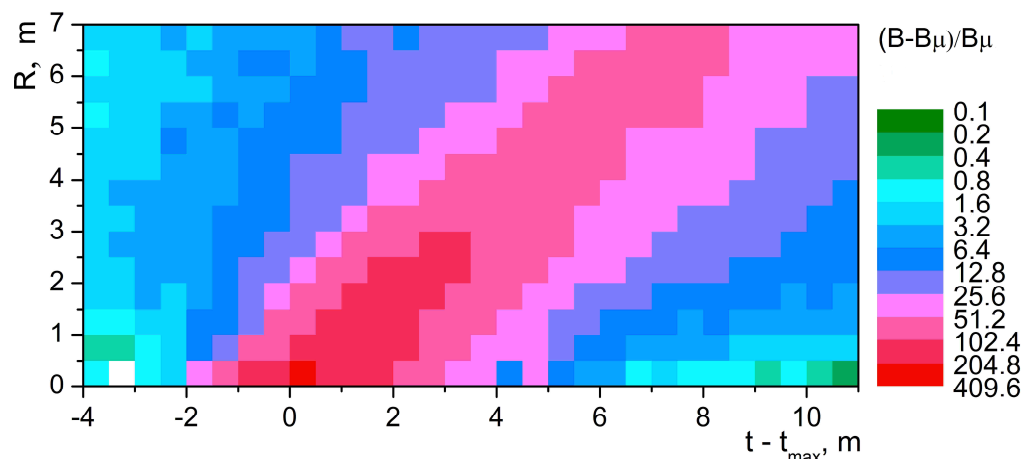

Figure 2. The dependence of Cherenkov light intensity from the showers normalized to the intensity from single muons.

For a further analysis of the influence of cascade particle scattering on the distribution of Cherenkov light, the dependence of $(B-B_\mu)/B_\mu$ value on the depth of shower for different distances was considered. Figure 3a shows longitudinal profiles of $(B-B_\mu)/B_\mu$ value for three intervals of distances from the axis of shower. Shifts and broadening of the profiles with the increasing distance are seen.
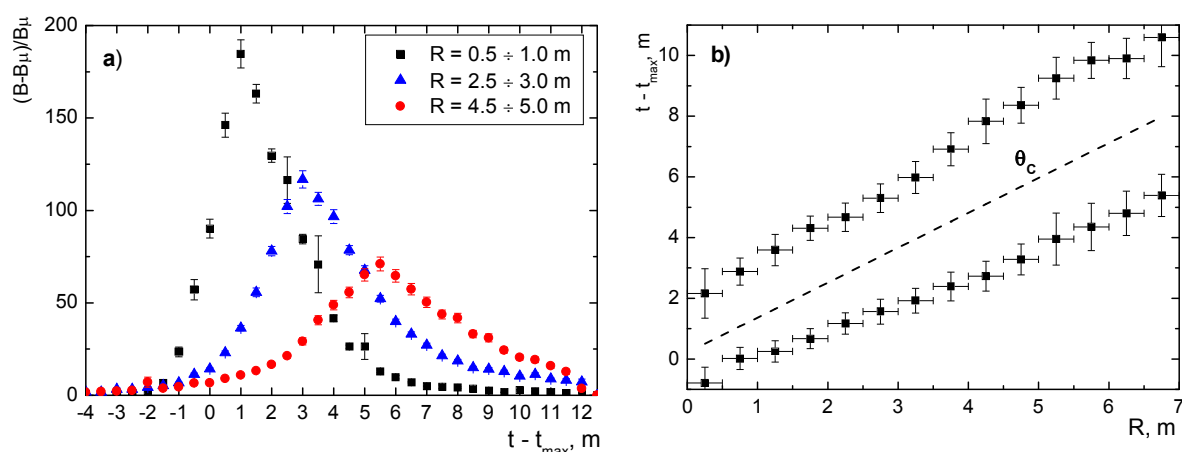

Figure 3. a) The longitudinal profiles of $(B-B_\mu)/B_\mu$ value for three intervals of distances from the axis of shower. b) The boundaries of longitudinal profiles at half of their maximum height for different distances from the axis. The dashed line shows the direction of Cherenkov radiation from particles moving strictly along the axis of the shower.

In details, these features are illustrated in plot 3b, where the points limiting the width of the profile at half maximum are shown as a function of the distance from the cascade axis. The plot shows that the width of the profile at half maximum at the distance of 7 m is almost doubled.

4. Conclusion

For the first time, the spatial distribution of Cherenkov light from cascade showers generated by muons in water has been experimentally measured at the CWD NEVOD with a dense lattice of quasi-spherical measuring modules. It has been found that the volume of highest light intensity has a compact shape with a radius of 1.5–2 m, which can be used for selection of cascades in the events with a large energy deposit in the Cherenkov detector.

Analysis of the results shows a good directivity of the light from the cascade at the angle close to the angle of Cherenkov radiation in water (approximately 41˚). This confirms the possibility of using the one-dimensional cascade model for the reconstruction of cascade curve by the response of the detector NEVOD at small distances from the axis (comparable to the length of the cascade).

On the other hand, the broadening of the Cherenkov cone related with the multiple scattering of cascade particles at larger distances from the shower axis is observed. These results can be used for verification and improvement of models of development of electromagnetic cascades in water and also for development of criteria of selection of cascade showers in Cherenkov water detectors and for reconstruction of their parameters.

Acknowledgements

References

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