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TECHNIQUE OF NEUTRINO-INDUCED MUON DETECTION ON THE EARTH SURFACE

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Methods of the rejection of atmospheric muon background for cosmic ray neutrino detection in a ground level Cherenkov water detector are described. The background rejection factor on the level 10^{10} is reached, and thereby a possibility to detect neutrino-induced muons on the Earth surface is shown.

Описана методика подавления фона атмосферных мюонов при регистрации нейтрино космических лучей в наземном черенковском водном детекторе. Получен фактор режекции фона на уровне 10 миллиардов, что подтверждает возможность регистрации мюонов, генерированных нейтрино, на поверхности Земли.

INTRODUCTION

To decrease the background of cosmic ray muons sophisticated neutrino telescopes are usually placed deep underground or underwater. At the same time, not less complex arrays are constructed on the Earth surface for studies of EAS and other components of cosmic rays. Therefore the idea to combine these types of detectors is very attractive. The main problem is related with very large background on the surface for rare neutrino events detection.

Theoretical considerations of this problem show that even on the Earth surface the interval of zenith angles exists, in which the flux of muons induced by neutrinos from the bottom hemisphere is larger than the flux of backward scattered near-horizontal atmospheric muons and of products of their interactions [1–3].

However, the grave technical problems connected with the necessity of selection of rare neutrino events from various kinds of background events still remain. Therefore measuring system of the set-up must provide the reliability of distinction of particle motion directions on the level better than 10^{10}.

In principle, Cherenkov Water Detectors (CWD) can provide such rejection factor by using the directionality of Cherenkov light. Besides, CWD of large area and volume can be constructed relatively easily. However, significant fluctuations of photomultiplier response at small fluxes of Cherenkov light, and hence the probabilistic nature of CWD response, create some difficulties in the reliable track reconstruction.

In the present work the technique of neutrino events selection at large atmospheric muon background is described. This technique was elaborated and tested by using experimental data collected with Cherenkov water detector NEVOD during experimental runs in 1996–1997.

1. EXPERIMENTAL ARRANGEMENT

NEVOD is the Cherenkov water detector on the Earth surface. General view of the first part of the set-up is given in Fig. 1. Crosses in the figure represent the quasispherical modules (QSM) which form nearly cubic spatial lattice with inner fiducial volume 6 × 6 × 7.5 m.

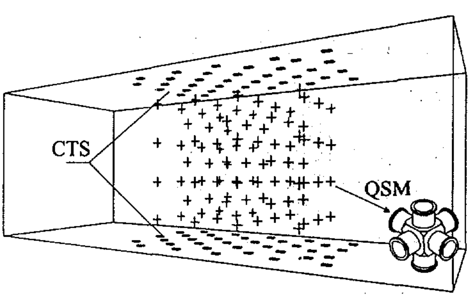

Fig. 1. Schematic view of NEVOD-91 set-up with 91 QSM and 2 × 32 scintillation counters

Detector description is presented in paper [4]. Hereafter only three basic systems of the set-up are described: QSM, triggering system and calibration telescope system (CTS). The parameters of these systems are especially important for the analysis of rare events.

Each quasi-spherical measuring module consists of six PMTs with flat photocathodes with 15 cm diameter. PMTs are directed along rectangular coordinate axes. The main feature of QSM is the possibility to determine the Cherenkov light direction on the basis of amplitude analysis only (without time-of-flight technique).

On the top and on the bottom of the tank, 2 × 32 scintillation counters are located, which form 1024 narrow angle telescopes. Telescope system allows one to select atmospheric muons in zenith angle interval from 0° up to 45°. The use of this telescope system gives the possibility to determine the NEVOD response for the passage of a single muon, and to calibrate the measuring modules.

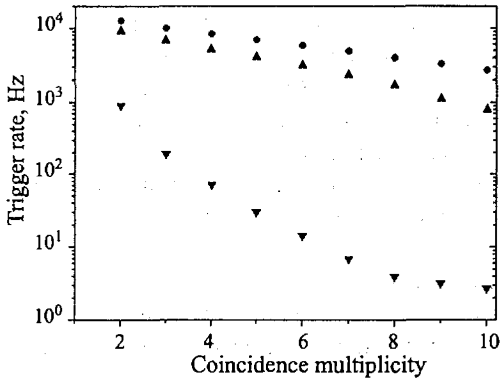

Fig. 2. Dependence of trigger rate on coincidence multiplicity: ● — trigger c; ▲ — trigger u; ▼ — trigger d

Two-level trigger system was used in the set-up. In each module, the coincidence of two adjacent PMTs within 80 ns time gate is required. The higher level trigger is based on the coincidences of signals between several modules, the number and location of which may be varied. In the present analysis, events selected with the following conditions were used: nd and nu correspond to coincidences of $\geqslant n$ quasi-spherical modules with hit downward- and upward-looking PMT, respectively; $t \times b$ is the telescope trigger, i. e., coincidences of any top (t) scintillation counter with any bottom one (b). Trigger d allows one to select events from the bottom hemisphere: Cherenkov radiation is detected by down-looking PMT. Organization of the trigger u is the same as d trigger (symmetrical triggers). It gives the possibility to use down-going atmospheric muons for estimation of d trigger efficiency. The dependence of basic trigger rates on the coincidence multiplicity is presented in Fig. 2. For the comparison,

c trigger rate (coincidences of signals from any triggered QSM) is also shown. This trigger allows to accept events from any direction.

The main operating time of the set-up includes the threshold coincidence multiplicity equal to 7. Under this condition, d trigger rate was about 5–6 Hz, and u trigger rate about 2 KHz. The rejection factor for downward going atmospheric muons on the trigger level was close to 300 (it was estimated as the ratio of counting rates for $7u$ and $7d$ triggers).

2. CALIBRATION EXPERIMENTS

The principle of v-induced events selection is based on the comparison of Cherenkov water detector response for downward and upward going muons taking into account the set-up symmetry.

Downward going atmospheric muons were selected with scintillation telescope trigger and u trigger. Data acquisition system provided the possibility to record each telescope event $(t \times b)$ during all the period of exposition. Set-up calibration with u trigger was conducted in two modes of operation. In 1996, the basic exposition with d trigger was switched off during such calibration. In 1997, collection of calibration data was realized without breakdown of the exposition. In this case, for reduction of u trigger rate from 2 KHz to an acceptable level, one event from every 4096 was selected on the hardware trigger level. The full set of calibration data contains about $2 \cdot 10^7$ telescope events and $\sim 10^7$ u trigger events detected during the expositions of 1996–1997.

2.1. Response for Vertical Muons. Using scintillation telescope trigger, the response for near vertical muons (0°–30°) was measured. An example of such event is shown in Fig. 3. It is possible to introduce the following parameters, which characterize the single muon response: N_0 — the total number of triggered modules, which allows one to separate muons and cascade showers; N_d — the number of down-looking PMT which in the case of near vertical down-going muons detection can be triggered, e. g., by dark noise, knock-on electrons and scattered light; ΔN_Z — difference of the number of QSM which show opposite directions of Cherenkov light in vertical; ΔN_X and ΔN_Y — differences between the numbers of QSM which show opposite directions along the set-up axes in horizontal plane; Z_{av} — average vertical coordinate of triggered QSMs. In Fig. 3, these parameters are shown for the displayed event. The average values of these parameters and typical ranges of their variation (about 90 % of the events) for telescope muons are given in Table 1.

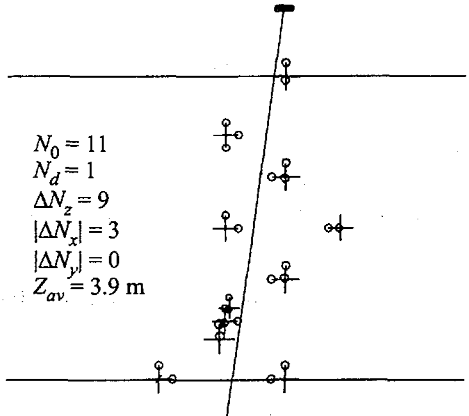

Fig. 3. Vertical muon event selected by calibration telescope. Hit phototubes are marked by the circles

Table 1. **Parameters of NEVOD response for near vertical telescope muons**

Parameter	Symbol	Average	Limits
No. triggered QSM	N_0	~ 12	7–18
No. down-looking PMT	N_d	~ 1	0–2
Difference of numbers of	ΔN_Z	~ 8	4–14
Triggered QSM indicating	ΔN_X	0	±4
Opposite directions	ΔN_Y	0	±4
Average Z-coordinate, m	Z_{av}	4.1	3.2–4.7

2.2. Reliability of Muon Motion Direction Reconstruction. From the point of view of selection of rare events from the bottom hemisphere in conditions of large background, the important characteristic of the set-up is the reliability of reconstruction of particle motion direction. In the first turn, this parameter depends on reliability of estimation of light direction by means of measuring modules. The reliability of this estimation is determined by detection system properties (PMT dark noise, cross-talks, etc.), by characteristics of water (absorption and scattering lengths), and by probability of the production of secondary particles by muon.

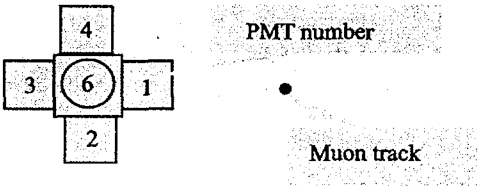

Fig. 4. Scheme of module calibration (top view)

Quantitatively, the reconstruction reliability is directly related with probabilities of various combinations of module PMT hits. For estimation of these probabilities, muons selected by scintillation telescope system were used. Only events with large fraction of hit PMTs that can detect direct Cherenkov light from the track (more 70 %) were used for analysis. This selection allows one to suppress multiparticle events. Experimental probabilities of various combinations of hit PMT of the measuring module are presented in Table 2 for vertical muon calibration (see Fig. 4).

Muon track was located at the distance equal to 1.25 m from the module centre. PMT No. 6 and No. 5 (not seen in Fig. 4) are directed up and down, correspondingly. Only PMT

Table 2. **Probabilities of various combinations of hit PMT in triggered QSM**

Combinations with up-looking PMT (No. 6)	6–1	6–2–1; 6–3–1	6–2; 6–4	6–2–3; 6–4–3	6–3
Average azimuth angle	0°	45°; 315°	90°; 270°	135°; 225°	180°
Experiment	0.81	$3.0 \cdot 10^{-2}$	$0.8 \cdot 10^{-2}$	$0.2 \cdot 10^{-3}$	$0.4 \cdot 10^{-2}$
Simulation	0.80	$3.1 \cdot 10^{-2}$	$1.0 \cdot 10^{-2}$	$0.2 \cdot 10^{-3}$	$0.5 \cdot 10^{-2}$
Combinations with down-looking PMT (No. 5)	**5–1**	**5–2–1; 5–3–1**	**5–2; 5–4**	**5–2–3; 5–4–3**	**5–3**
Experiment	$3.0 \cdot 10^{-2}$	$0.9 \cdot 10^{-3}$	$0.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-5}$	$0.6 \cdot 10^{-3}$
Simulation	$2.9 \cdot 10^{-2}$	$1.1 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$0.4 \cdot 10^{-5}$	$0.7 \cdot 10^{-3}$

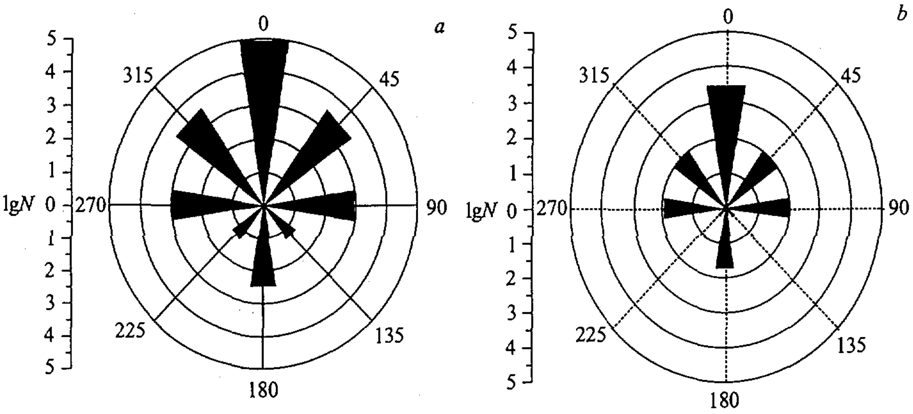

Fig. 5. Azimuth diagrams of measuring module response: *a*) combinations with up-looking hit PMT; *b*) with down-looking hit PMT

No. 1 and No. 6 can detect direct Cherenkov light. Each combination of triggered PMT corresponds to a different average azimuth angle indicated by a measuring module. Examples of averaged azimuth diagrams of the module response are presented in Fig. 5. The results of module response simulation for identical conditions are presented in Table 2, too. Simulation data are in a reasonable agreement with the experiment.

On the basis of calibration experiments and simulation data, it is possible to calculate the probability of observation of a given response as a function of track location $P(\theta, \xi) \equiv P$ (response$\,|\,\theta, \xi$), where θ is zenith angle, ξ is the vector of other track parameters. Examples of $P(\theta, \xi)$ averaged over ξ are presented in Fig. 6 for two calibration muon events with θ about 0° and 30°.

For nearly isotropic muon flux this probability function $P(\theta, \xi)$ could be used for maximum likelihood estimation of track parameters. However, in conditions of the heavily changing flux (the order of 10^{10} in the case of up-going muon reconstruction), plain likelihood technique can lead to a serious error of zenith angle estimate. To prevent such mistakes, the conditional probability $F(\theta\,|\,\text{response})$ that takes into account the realistic zenith angle distribution of muons was used for individual event analysis:

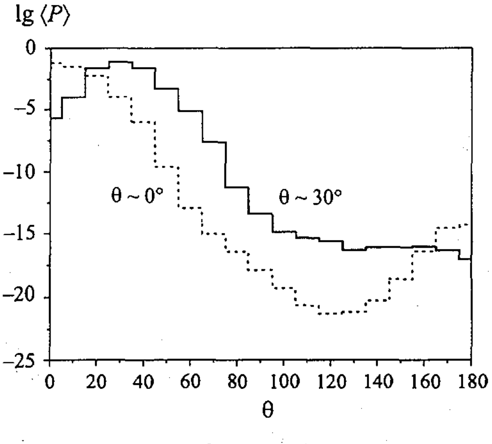

Fig. 6. Examples of averaged probability functions $P(\theta)$ calculated for a vertical muon and an inclined one (arb. units)

$$\frac{dF(\theta)}{d\cos\theta} = \frac{\int\limits_{\xi} I_\mu(\theta)P(\theta,\xi)d\xi}{\int\limits_{\theta,\xi} I_\mu(\theta)P(\theta,\xi)d\cos\theta d\xi}, \tag{1}$$

where $I\mu(\theta)$ is the intensity of muons near the Earth surface (mainly atmospheric muons up to 90°, scattered muons from 90° to 120°, neutrino-induced muons for angles more than 120°). The position $\tilde{\theta}$ of maximum of the conditional probability distribution is determined both by the angular dependence of muon flux and by $P(\text{response}\,|\,\theta,\ \xi)$.

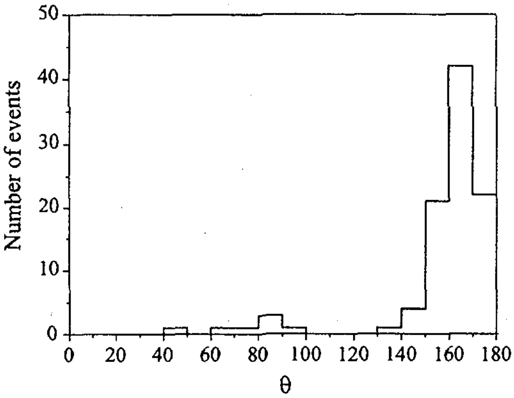

Fig. 7. Distribution of $\tilde{\theta}$ for turned-over (mirror) events

Taking into account the detector symmetry, calibration data were used for investigations of conditional probability distributions for upward going muons. For this purpose, calibration events ($7u$ trigger with some additional cuts discussed in section 3.2) were turned-over (mirror events), and distributions $F(\theta\,|\,\text{response})$ were calculated. Distribution of the value of $\tilde{\theta}$ corresponding to the maximum of $F(\theta\,|\,\text{response})$ for 100 mirror events is presented in Fig. 7. One can see that more than 90 % selected mirror events are reconstructed as up-going muons. It evidences for the possibility of selection of real up-going muons in the NEVOD set-up.

3. EXPERIMENTAL STUDIES

For experimental study of possibilities to detect neutrino-induced muons on the Earth surface in Cherenkov water detectors, series of experiments was conducted with NEVOD set-up in 1996–1997. The total net operation time was more than $2 \cdot 10^3$ h., $3.4 \cdot 10^7$ events were recorded with $7d$ trigger. Total number of atmospheric muons that could be detected with trigger $7u$ during this period was about 10^{10}. Obtained experimental material permits to investigate the main sources of neutrino-induced event imitations and to analyze the possibilities of neutrino detection.

The experimental data treatment included the following main stages: data cleaning, event selection on the basis of simple fast criteria, and subsequent consideration of selected events. The final objective of the analysis was the search of neutrino event candidates.

3.1. Experimental Data Cleaning. Preliminary data cleaning was conducted during experimental runs and data base accumulation. The runs which contained malfunctions in measuring system operation were excluded. The main objective of the off-line data cleaning was the exclusion of separate unreliable measuring modules from the analysis. Taking into account the necessity of selection of rare events, measuring module was excluded if probability of a false hit of any its PMT was more than 10 %. Estimation of these probabilities was made on the basis of results of scintillation telescope calibration. As an example, time dependence of the number of excluded modules is presented in Fig. 8 for one of the periods of the exposition. Additionally, this analysis allows one to exclude the periods of exposition with abnormally large number of unreliable QSM.

3.2. Fast Criteria for Event Selection. The parameters listed in Table 1 (Section 2.1) can be used for preliminary upward-going muon selection. At the choice of critical values of these parameters it is necessary to take into account that narrow interval of parameter values results in a higher rejection factor but lower efficiency of useful event selection, and vice versa. As a compromise, the criteria presented in Table 3 were chosen for upward-going muon selection. Additional parameter N_{out} (the number of triggered QSM in external planes of the set-up looking out of the fiducial volume) was introduced to exclude the events, which are generated outside of the sensitive volume, mostly in the areas along the water tank. The corresponding background rejection factors f_R are given in Table 3, too. The combined rejection factor for this preliminary selection is about 10^5.

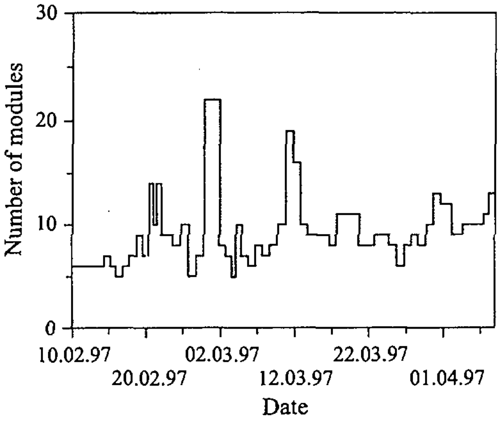

Fig. 8. The number of modules excluded from the analysis vs. time

Table 3. **Criteria for upward-going muon selection**

Parameter	Range	f_R	Comments
N_0 N_d ΔN_Z	8–20 $\leqslant 2$ $\leqslant -8$	~ 30	Exclude noise and showers, and indicate particle motion direction
$\lvert\Delta N_X\rvert$ $\lvert\Delta N_Y\rvert$ N_{out}	$\leqslant 4$ $\leqslant 4$ $\leqslant 2$	~ 80	Select muons crossing central part of the fiducial volume
Z_{av}	> 3.7	~ 40	Suppresses near-horizontal muons
Combined rejection factor		$\sim 10^5$	

As a result, 328 events (of $3.4 \cdot 10^7$) remained after selection with these criteria. The *probability to lose useful events was about 65 % (i. e., 35 % selection efficiency). This* efficiency was estimated both with scintillation telescope events (35 %) and events selected with $7u$ trigger (34 %).

3.3. Analysis of Selected Events. The classification of selected events was performed on the basis of the track reconstruction made under assumption that single muons were detected. Two main parameters obtained with this procedure were used for the analysis:

- θ — reconstructed zenith angle of the track;
- r — the ratio of the number of hit PMT which can detect direct Cherenkov light from the reconstructed track to the number of all triggered PMT.

Distribution of events in the values of these parameters is presented in Table 4.

Table 4. **Classification of selected events**

θ	r	Number of events		
		1996	1997	Total
Any	$\leqslant 0.7$	46	78	124
$< 120°$	> 0.7	66	126	192
$\geqslant 120°$	> 0.7	4	8	12

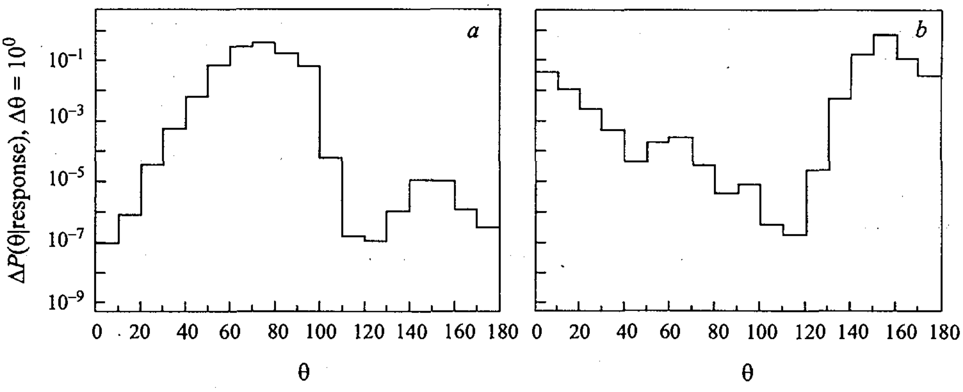

Fig. 9. Examples of $F(\theta\,|\,\text{response})$ for two of selected events

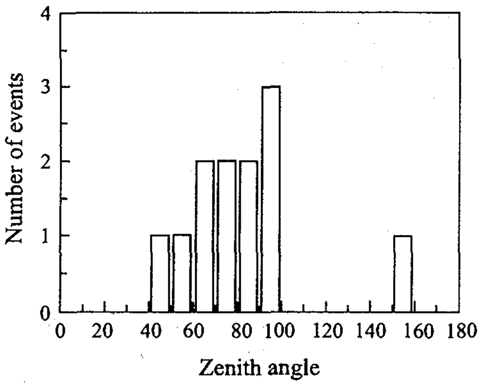

Fig. 10. Distribution of 12 selected events in zenith angle estimation

About 40 % of selected events have the value of r less than 0.7. At the same time, for real muons 95 % of events satisfy the condition of $r > 0.7$ for $7u$ trigger, and 93 % for telescope trigger. The low value of r indicates that this group of events does not correspond to single muons. Most part of these events may be interpreted as muon groups, showers, and random muon coincidences.

The second group of events (somewhat less than 60 %) contains mainly near-horizontal muons.

Only the third group (12 events) can contain neutrino candidates and is interesting for the subsequent analysis. For all events of this group the conditional probabilities of various zenith angles at a fixed response $F(\theta\,|\,\text{response})$ were calculated (under the same assumption that they are single muons). The zenith angle distribution of muons near the Earth surface was taken into account for this estimations (see Eq. (1)). Typical examples of θ distributions are presented in Fig. 9. Eleven events have a character of distribution similar to that shown in Fig. 9, *a* (two peaks, global maximum near 90°). These events can be interpreted as near-horizontal atmospheric muons. Only one event has maximum of probability distribution in the range of zenith angle greater than 120° (Fig. 9, *b*).

The distribution of zenith angles $\tilde{\theta}$, which correspond to the maximum of $F(\theta \mid \text{response})$, is shown in Fig. 10 for all 12 selected events. Only one event can be regarded as neutrino event candidate — zenith angle estimation is about 150° (see Fig. 9, *b*).

4. DISCUSSION

In the frame of the present analysis, selection of the upward-going muons included the following steps:

— primary experimental data were selected with $7d$ trigger which provided the background rejection factor about 300;

— fast criteria of event selection elaborated on the basis of the analysis of single muon response taking into account the set-up up-down symmetry were applied (rejection factor $\sim 10^5$);

— the individual analysis of events was conducted on the basis of track reconstruction and calculations of the conditional θ distributions for the given response (rejection factor ~ 300).

As a result of the analysis of experimental data, one candidate for neutrino-induced muon was selected. The experimental estimation of the number of atmospheric muons that crossed fiducial volume of detector during the time of the exposition was about 10^{10}. So, the rejection factor of atmospheric muons on the level 10^{10} has been reached with Cherenkov water detector NEVOD.

Full set of criteria for neutrino candidates provides the efficiency of useful event selection equal to 30 %, which is determined by 35 % efficiency of fast criteria, 95 % efficiency of track reconstruction and about 90 % efficiency of probabilistic analysis (Fig. 7). Systematic uncertainty of the efficiency estimation can arise from some up-down asymmetry of the NEVOD set-up. Firstly, the water layer under the measuring modules lattice is slightly more than the water layer over it. Secondly, because of sediments on photocathodes of up-looking

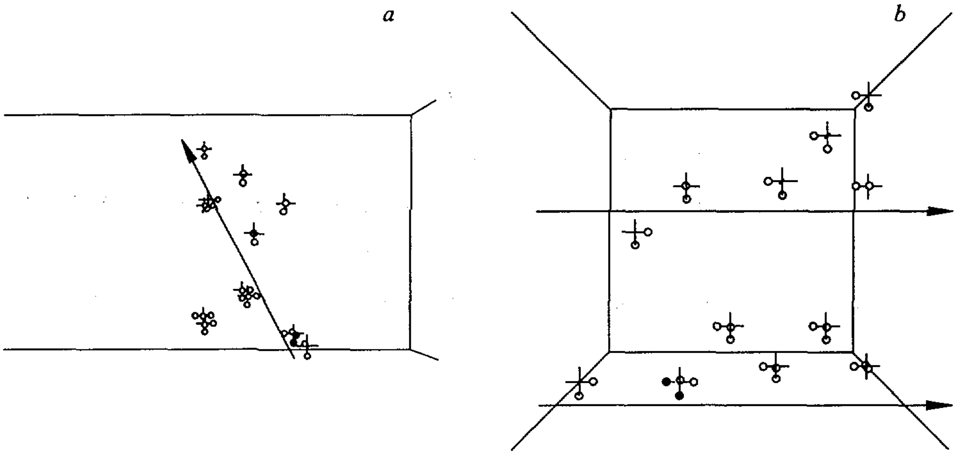

Fig. 11. Possible interpretations of the neutrino event candidate: *a*) front view; *b*) side view

PMT during long-time experiment, the sensitivity of down-looking PMT is somewhat higher on the average. It is necessary to underline, that both these factors lead to the increase of the efficiency of useful event selection.

There is a question: is the selected neutrino candidate the real neutrino event? In this connection it is important to note that all the criteria of event selection are necessary but not sufficient conditions for interpretation of the event as neutrino-induced muon. In particular, zenith angle probability distributions for events were calculated without taking into account correlations between measuring module responses. Besides, a priori information was used that all events were single muons. However, more complicated events also could be detected during the exposition and could pass the selection criteria. As an example, in Fig. 11 two possible interpretations of the selected neutrino candidate are presented: neutrino-induced muon from the bottom (Fig. 11, *a*) and pair of near-horizontal muons (Fig. 11, *b*).

CONCLUSION

The analysis of upward-going muon imitations showed that the most significant source of the background is represented by near-horizontal muons.

The described technique of the events selection has provided the suppression of atmospheric muon background with a rejection factor on the level of 10^{10}. Thus, the possibility to detect high energy neutrinos with Cherenkov water detectors on the Earth surface is shown. The relatively low efficiency of useful event selection obtained in the present configuration of the detector (about 30 %) was caused by a small thickness of the fiducial volume (6 m). The efficiency can be significantly improved with the increase of the set-up sizes.

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