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Results from the Baikal Underwater Telescope

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presented by S.I.Klimushin

Since one and a half year, the underwater Cherenkov telescope NT-36 consisting of 36 photomultipliers attached to 3 strings is operated in lake Baikal. The large statistics of collected data allows for comparison with Monte Carlo predictions starting from the level of detector response up to more sophisticated dependences like the angular distribution of muon intensity.

The Baikal Neutrino Telescope [1-2] is being deployed in the Siberian Lake Baikal, about 3.6 km from shore at a depth of 1.1 km.

Since April 13th, 1993 we have been operating the stationary 3-string detector *NT-36*. Since April 3th, 1994 a modified version, *NT-36'* is taking data. These arrays with 36 optical modules are the first step towards the Neutrino Telescope *NT-200* [2] which will consist of a total of 192 optical modules.

The 3 strings of NT-36 are attached to a mechanical frame which later will carry the 8 strings of NT-200 (Fig.1). Two underwater electrical cables and one optical cable connect the detector site with the shore station. Deployment of all detector components is carried out during 7 weeks in late winter when the lake is covered by a thick layer of ice.

The optical modules are equipped with the QUASAR-370, a 37 cm diameter phototube[3]. They are grouped in pairs along the strings, directed alternatively upward and downward. The distance between pairs looking face to face is 7.5 m, while pairs arranged back to back are 5 m apart. There are 6 pairs along each of the 3 strings of NT-36. The two PMTs of a pair are connected in coincidence and define a *channel*, giving 18 channels for the NT-36 detector. The typical 1 *p.e.* counting rate due to noise and bioluminescence is 50-100 kHz for a single QUASAR. By the coincidence, the rate is reduced to 100-300 Hz per pair.

A *muon-trigger* is formed by the requirement of ≥ 3 fired channels within a time window of 500 nsec. For such events, amplitude and time of all fired channels are digitized and sent to shore. A second system (*monopole trigger*) searches for time patterns characteristic for slowly moving, bright particles.

For trigger 6/3 (i.e. ≥ 6 hits at 3 strings), suitable for unambiguous track reconstruction, the effective area of NT-36 is calculated to be about 270 m^2 for 1 TeV muons. For 10 TeV muons it rises to 1000 m^2. With a trigger threshold of 10 GeV

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the average effective area for atmospheric muons is 146 m^2, giving an expected counting rate for atmospheric muons of $4.5 \cdot 10^7$ per year. 60 events per year are expected for muons from neutrino interactions coming from the lower hemisphere (trigger 6/3).

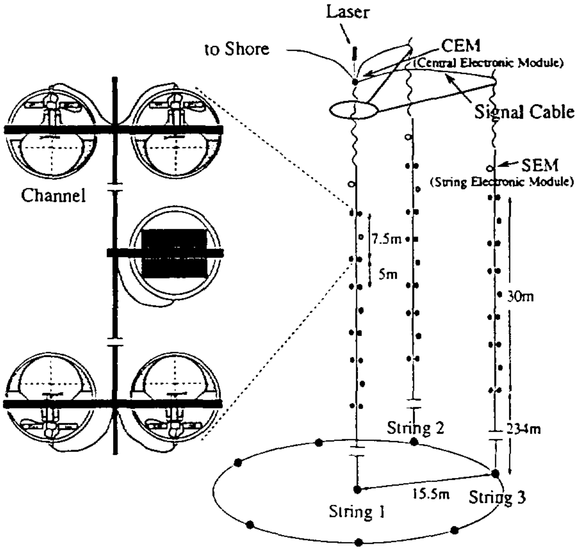

Fig.1. Schematical view of NT-36. Two PMTs form a channel, 2 channels are controlled by an "electronic module". The black dots at the bottom indicate the position of the future strings nb.4-8 of NT-200.

The array came into operation on April 13th, 1993 and was operated up to March 1994. The main muon data taking runs were interrupted only due to calibration runs, operation of the environmental units, power failures and thunderstorms.

During 240 days of data taking, $7 \cdot 10^7$ events for the basic trigger 3/1 (10 Hz for all channels operational) have been taken, 10^7 of them fulfilling the trigger condition 6/3 (2.8 Hz). Just before the 1993 array was hauled up (March 1994), 23 of the 36 Optical Modules were still in operation. 9 OMs were dead and 4 were not accessible due to a failure of a controller module. Altogether, 9 out of the originally 18 channels were still in operation. Losses have been due to failures of electronic components. All QUASAR-370 turned out to be still operational. None of the pressure housing had leaked.

A modified array, *NT-36'*, came into operation on April 3th, 1994 and is still working. During 125 days, $5 \cdot 10^7$ events have been taken up to now. 31 out of 36 OM (14 out of 18 channels) are still operating.

The experimental data presented below are from the early summer 1993 when 16 channels have been operating ($1.5 \cdot 10^6$ events). Some of the results have been presented more detailed in refs. [4,5].

Fig. 2 shows the amplitude distributions for channels 7 and 8. Note that the good agreement between MC and experiment is obtained only for correct modelling of the effects of δ-electrons and electromagnetic showers accompanying the muon.

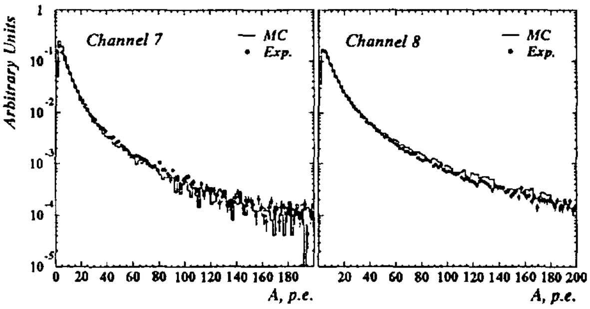

Fig.2. Amplitude distributions for channels 7 and 8. Points: experimental data, solid line: MC results - atmospheric muons including full energy loss.

Fig.3 shows the distribution of light arrival time differences, Δt_{ij}, for different channel combinations. Monte Carlo and experiment are found to coincide quite well for most channels. However, there are combinations showing deviations part of which are not fully interpreted up to now.

With a reasonable understanding of integral amplitude and time characteristics of the experimental data, track reconstruction may be envisaged. The reconstruction procedure consists of the following steps[6]:

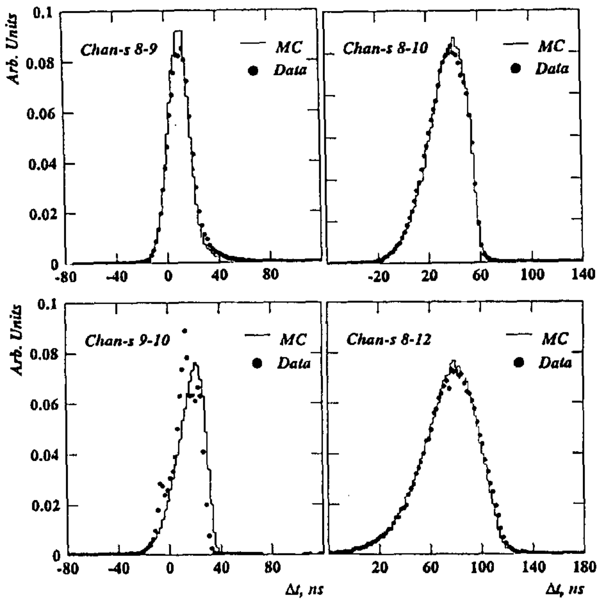

Fig.3. Distribution of light arrival time differences $\Delta t_{ij} = t_i - t_j$ for different channel combinations. Points are experimental data, MC results are given by the solid line.

- preliminary analysis including causality criteria rejecting events violating the model of a naked muon, and a 0th approximation,
- χ^2 minimum search, using only time information,
- application of criteria to reject badly reconstructed events (error matrix analysis, amplitude criteria, etc.),
- application of dedicated *up/down* criteria applied only if searching for upward muons from *neutrino interactions.*

Fig.4 shows the distribution of the zenith mismatch angle $\Delta\Theta$ as obtained from MC calculations. Note that the long tail with large mismatch angles is substantially lowered by application of stringent quality criteria [6]. The medium zenith mismatch angle for the given set of cuts was obtained to be 5.3° before and 1.6° after application of the quality criteria. The errors for the spatial mismatch angle are 12.3° and 4.0°, respectively. Note that these values are rather conditional: with stronger cuts the resolution improves but the effective area decreases.

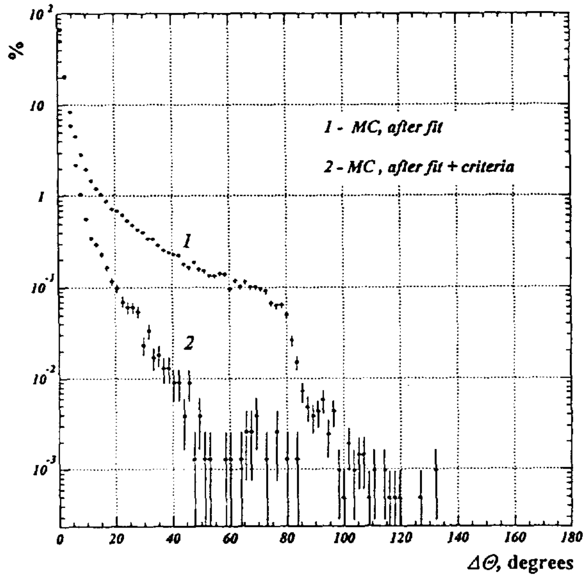

Fig.4. Distribution of the zenith mismatch angle $\Delta\Theta$ for NT-36 obtained from MC simulations.

In Fig.5, the zenith angle distribution for the reconstructed muons, having passed all cuts is shown. A rather satisfying agreement between experimental and MC data is observed.

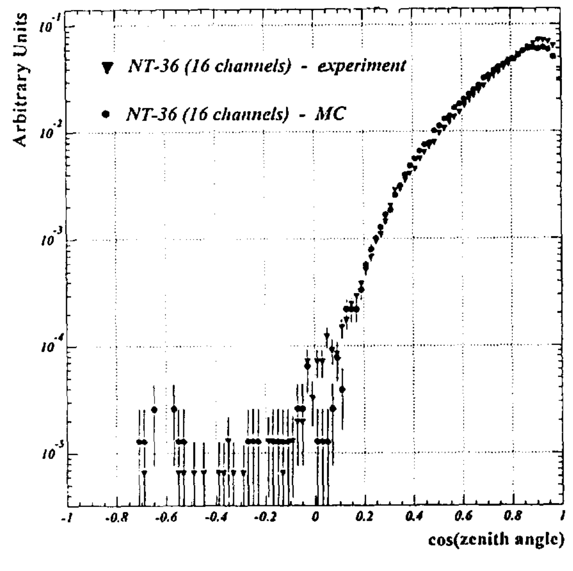

Fig.5. Zenith angle distribution for reconstructed muons after application of quality criteria (but without up-down cuts!). Full circles: MC, triangles: experiment.

A portion of $1.5 \cdot 10^{-4}$ of the initial sample is reconstructed as upward going muons, again with a good agreement between MC and experiment. Starting from an initial down-to-up ratio of 10^6, the ratio of fake events to muons from atmospheric neutrinos is $10^6 \cdot 1.5 \cdot 10^{-4}/0.4 \approx 3 \cdot 10^2$(with 0.4 being the passing rate of neutrino-induced upward muons). With additional up/down criteria tailored to separate upward events, this ratio has been decreased down to 50. The agreement of the results from NT-36 with MC calculations support our confidence based on simulations of NT-200, namely, that an underwater array consisting of 200 PMTs at 1 km depth can be operated as a neutrino telescope.

Convoluting the zenith angle distribution with the known zenith angle dependence of the effective area, the ratio of MC and experimental survival rates and the distortion function, one obtains the experimental angular distribution of the muon intensity. The angular dependence of the muon flux $I_{L_0}(\Theta)$ at a given depth L_0, can be transformed into the depth dependence of the vertical flux $I_L(0)$ at different depthes L. Fig.6 shows a comparison of our results obtained by this procedure with other published values of $I_L(0)$ (see, for the references, ref. [7]) as well with the depth-intensity curve calculated in [8].

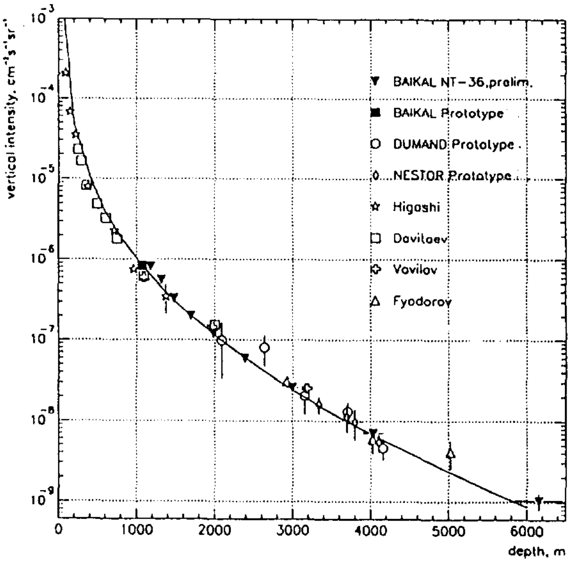

Fig.6. Vertical muon flux, $I_L(0)$, vs. water depth.

In parallel to the high energy neutrino and muon programme, we perform a search for slowly moving, bright particles like magnetic monopoles or strange quark nuclearities. From monopole induced proton decays [9] we would expect Cherenkov light signals generated by the decay products. For certain regions of the parameter space in β (monopole velocity) and σ_c (catalysis cross section), GUT monopoles would cause sequential hits in individual channels in time windows of 10^{-4} - 10^{-3} sec. We have searched for such enhanced counting rates and deduce an upper limit for the flux of monopoles catalyzing the decay of free protons with cross section $\sigma_c = 0.17 \cdot \sigma_o \cdot \beta^{-2}$. For instance, with $\sigma_o = 10^{-29}$ cm^2 and $\beta = 10^{-4}$ one gets a flux limit of 10^{-15} cm^{-2} sec^{-1} sr^{-1}, just at the Chudakov-Parker limit and of the same order of magnitude as the limits obtained by our collaboration with dedicated setups in 1984-89 [10].

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