THE BAIKAL EXPERIMENT: STATUS REPORT

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We review the present status of the Baikal Neutrino Project. The construction and performance of the large deep underwater Cherenkov detector for muons and neutrinos, *NT-200*, which is currently under construction in Lake Baikal are described. Some results obtained with the first stages of *NT-200* – *NT-36* (1993-95), *NT-72* (1995-96) and *NT-96* (1996-97) – are presented, including the first clear neutrino candidates selected with 1994 and 1996 data.

1 Introduction

The possibility to build a neutrino telescope in Lake Baikal was investigated since 1980, with the basic idea to use – instead of a ship – the winter ice cover as a platform for assembly and deployment of instruments[1]. After first small size tests, in 1984-90 single-*string* arrays equipped with 12 – 36 PMTs (*FEU-49* with flat 15 cm photocathode) were deployed and operated via a shore cable[2]. The total life time for these "first generation detectors" made up 270 days. On the methodical side, underwater and ice technologies were developed, optical properties of the Baikal water as well as the long-term variations of the water luminescence were investigated in great details. For the Baikal telescope site the absorbtion length for wavelength between 470 and 500 nm is about 20 m, typical value for scattering length is 15 m[a] with mean cosine of the scattering angle being close to 0.95 (see[3] and refs. therein). Since 1987, a "second generation detector" with the capability to identify muons from neutrino interactions was envisaged. Tailored

[a]Sometimes the *effective scattering length* $L_{eff} = L_{scatt}/(1 - \langle\cos\theta\rangle)$ is used to characterize the relative merits of different sites for neutrino telescopes[4]. With L_{scatt}= 15 m and $\langle\cos\theta\rangle = 0.95$ one obtains $L_{eff} = 300$ m for the Baikal site.

to the needs of the Baikal experiment, a large area hybrid phototube *QUASAR*[5] with hemispherical photocatode of 37 cm diameter and a time resolution of better than 3 nsec was developed to replace *FEU-49*. According to the approximate number of PMTs this detector was named *NT-200* – Neutrino Telescope with 200 PMTs[6]. With estimated effective area of about 2300m^2 and 8500m^2 for 1-TeV and 100-Tev muons, respectively, it is a first stage of a future full-scale telescope, which will be built stepwise, via intermediate detectors of rising size and complexity.

2 The Baikal Neutrino Telescope *NT-200*

The Baikal Neutrino Telescope (Fig.1) is being deployed in Lake Baikal, 3.6 km from shore at a depth of 1.1 km. It will consist of 192 optical modules (OMs). The umbrella-like frame carries the 8 strings with the detector components. The OMs are grouped in pairs along the strings. The pulses from two PMTs of a pair after 0.3 *p.e.* discrimination are fed to a coincidence with 15 ns time window. A pair defines a *channel*. A *muon-trigger* is formed by the requirement of $\geq N$ *hits* (with *hit* refering to a channel) within 500 ns. N is typically set to the value 3 or 4. Then digitized amplitudes and times of all hit channels are sent to the shore. A separate *monopole trigger* system searches for time patterns characteristic for slowly moving objects.

In April 1993, the first part of *NT-200*, the detector *NT-36* with 36 OMs at 3 short strings, was put into operation and took data up to March 1995. A 72-OMs array, *NT-72*, run in 1995-96. In 1996 it was replaced by the four-string array *NT-96*. Summed over 700 days effective life time, $3.2 \cdot 10^8$ muon events have been collected with *NT-36, -72, -96*. Since April 6, 1997, *NT-144*, a six-string array with 144 OMs, is taking data in Lake Baikal.

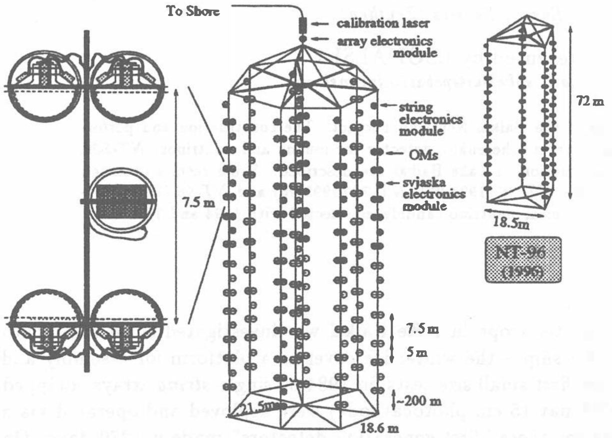

Figure 1: Schematic view of *NT-200*. Components deployed in 1993 are in black, those added in 1995 in grey. Top right: the strongly modified array deployed in 1996.

3 Track Reconstruction

In contrast with a typical underground detector, it is impossible to determine co-ordinates for some clearly visible points which would belong to a track of a particle crossing an underwater array because it represents a lattice of OMs with large distances between them. The parameters of a single muon track have to be determined[7] by minimizing

$$S_t^2 = \sum_{i=1}^{N_{hit}} (T_i(\theta, \phi, u_0, v_0, t_0) - t_i)^2 / \sigma_{ti}^2.$$

Here, t_i are the measured times and T_i the times expected for a given set of track parameters. N_{hit} is the number of hit channels, σ_{ti} are the timing errors. A set of parameters defining a straight track is given by θ and ϕ – zenith and azimuth angles of the track, respectively, u_0 and v_0 – the two coordinates of the track point closest to the center of the detector, and t_0 – the time the muon passes this point. For the results given here we do not include an amplitude term S_a^2 analog to S_t^2 in the analysis, but use the amplitude information only to calculate the timing errors σ_{ti} in the denominator of the formula above. Only events fulfilling the condition "≥ 6 hits at ≥ 3 strings" are selected for the track reconstruction procedure which consists of the following steps:

1. A preliminary analysis includes several causality criteria rejecting events which violate the model of a naked muon. After that, a 0-th approximation of θ and ϕ is performed.

2. The χ^2 minimum search, based on the model of a naked muon and using only time data.

3. Quality criteria to reject most badly reconstructed events.

We have developed a large set of pre-criteria as well as quality criteria to reject misreconstructed events. Most of these criteria are not independent of each other. Furthermore, the optimum set of criteria turned out to depend on the detector configuration. The causality criteria refer to time differences between channels. *E.g.*, one requests that each combination of two channels i, j obeys the condition $c\,|dt_{ij}| < n\,|dx_{ij}| + c\,\delta t$, where dt_{ij} and dx_{ij} are time differences and distances between channels i and j, respectively and $n = 1.33$ is refraction coefficient for the water. The term $\delta t = 5$ nsec accounts for time jitter. Some of the most effective quality criteria are, *e.g.*, upper limits on parameters like the minimum χ^2, the probability P_{nohit} of non-fired channels not to respond to a naked muon and probability P_{hit} of fired channels to respond to a naked muon.

4 Selected Results

4.1 Atmospheric Muons Vertical Flux

Muon angular distributions are well described by MC expectations. Converting the measured angular dependence obtained with standard reconstruction applied to *NT-36* data[3] into a depth dependence of the vertical flux, good agreement with theoretical predictions is observed (Fig.2).

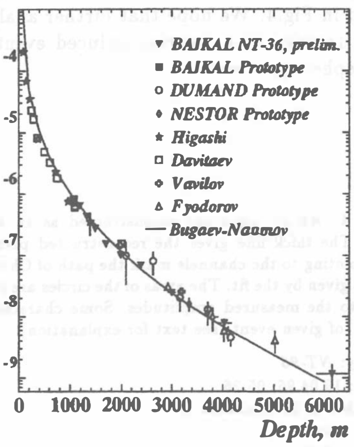

Figure 2: Vertical muon flux, $I_\mu(cos\theta = 1)$, vs. water depth L. The five *NT-36* values (full triangles) are calculated for $\cos\theta =$ 0.2 to 1.0 in steps of 0.1. The curve represents theoretical predictions[8]. The other data points are taken from refs. [9].

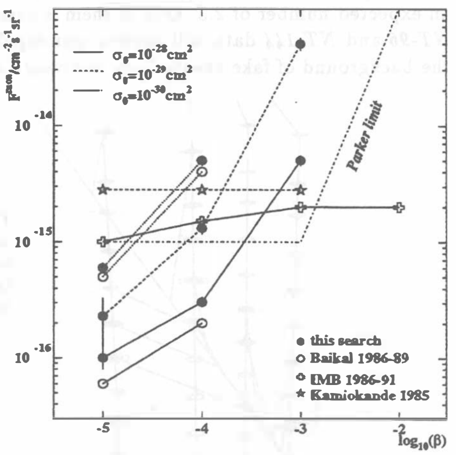

Figure 3: Upper limits (90 % CL) on the natural flux of magnetic monopoles catalyzing barion decqay versus their velocity β, for different parameters σ_o, see text.

4.2 Upper Limits on the Flux of Monopoles Catalyzing Baryon Decay

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. Having searched for such enhanced counting rates in the 1993 data obtained with *NT-36* array we deduce upper limits for the flux of monopoles catalyzing the decay of protons with cross section [10] $\sigma_c = 0.17 \cdot \sigma_0 \cdot \beta^{-2}$. Our limits (90 % CL) are shown in Fig.3 together with our earlier results [2], limits from IMB [11] and Kamiokande [12] and with the astrophysical Chudakov-Parker limit [13]. A limit of $4 \cdot 10^{-16}$ cm^{-2} s^{-1} has been obtained by the Baksan Telescope [14] for $\beta > 2 \cdot 10^{-4}$. Further progress is expected with the next stages of *NT-200*.

4.3 Separation of Neutrino Events with Standard Track Reconstruction

The most obvious way to select events from the lower hemisphere (which dominantly are due to atmospheric neutrino interactions in the ground or water below the array) is to perform the full spatial track reconstruction (see Sec. 3) and select the events with negative θ values. Taking into account that the flux of downward muons is about 6 orders of magnitude larger than the flux of upward muons, the reconstruction procedure should be performed extremely thoroughly. Even if very small fraction of downward atmospheric muons is misreconstructed as up-going ones, it forms an essential background. Due to small value of S/N ratio (where S is counting rate of upward neutrino induced events and N is counting rate of downward atmospheric muons which are reconstructed as upward events), it is impossible to observe clear neutrino signal with *NT-36* and *NT-72* data and the current level of standard reconstruction procedure. MC calculations indicate the essetially better characteristics for *NT-96* detector which can be considered as a neutrino telescope in the wide region of θ. The analysis of the *NT-96* data aimed to search for the upward neutrino induced muons using the standard reconstruction procedure is presently in progress. The reconstruction procedure is tuned in this first analysis to a 60 degree half-aperture cone around the opposite zenith. 1.2 neutrino induced events per week are expected from MC calculations. We have analyzed 12.9 days data sample and selected 3 neutrino candidates with an expected number of 2.3. One of them is presented in Fig.4. We hope that further analysis of *NT-96* and *NT-144* data will confirm our capability to select the neutrino induced events over the background of fake events from downward atmospheric muons.

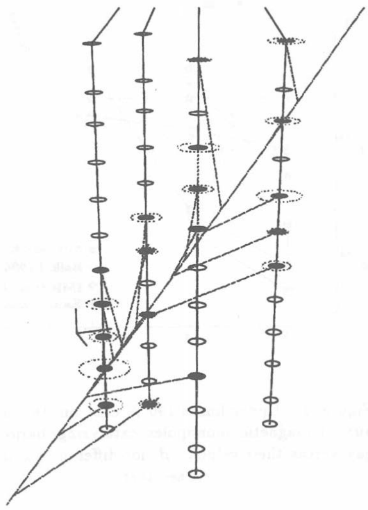

Figure 4: An *NT-96* event reconstructed as an upward muon. The thick line gives the reconstructed path, thin lines pointing to the channels mark the path of Cherenkov light as given by the fit. The areas of the circles are proportional to the measured amplitudes. Some characteristics of given event (see text for explanation):

Array: *NT-96*
Date: 19.04.96; 05:26
Number of hit channels: 19
P_{hit}: 0.38
P_{nohit}: 0.75
χ^2_{time}/NDF: 0.48
χ^2_{ampl}/NDF: 1.2
Max. dist. between hit channels: 72.6 m
Reconstructed θ: -152.7 deg.
Reconstructed ϕ: 253.5 deg.

4.4 Search for Nearly Upward Moving Neutrinos

To identify nearly vertically upward muons with energies below 1 TeV (as expected, *e.g.*, for muons generated by neutrinos resulting from dark matter annihilation in the core of the Earth), full reconstruction is found to be not neccessary [15]. Instead, separation criteria can be applied which make use of two facts: firstly, that the muons searched for have the same vertical direction like the string; secondly, that low-energy muons generate mainly direct Cherenkov light and, consequently, are not visible over large distances and should produce a clear time and amplitude pattern in the detector. We have choosen the following separation criteria:

1. 3 down-facing and at least 1 up-facing channels at one string exclusively must be hit with time differences between any 2 hit channels i and j obeying the condition $|(t_i - t_j) - (T_i - T_j)| < 20ns$, where $t_i(t_j)$ are the measured times, $T_i(T_j)$ are the times expected for minimal ionizing, up-going vertical muons.

2. The signals of down-facing channels should be significantly larger than those of upward facing channels. Any combination of oppositely directed hit channels must obey the inequality $(A_i(\downarrow) - A_j(\uparrow))/(A_i(\downarrow) + A_j(\uparrow)) > 0.3$ with $A_i(\downarrow)$ and $A_j(\uparrow))$ being the amplitudes of channels i and j facing down and up, respectively.

3. All signals of down facing channels must exceed a minimum value of 4 *p.e.* (this prevents that the previous cut is dominated by low amplitude events and, consequently, by fluctuations of the few-photoelectron statistics).

The analysis presented here is based on the data taken with *NT-36* during the period April 8, 1994, to March 1, 1995 (212 days of detector life time). Upward-going muon candidates were selected from a total of $8.33 \cdot 10^7$ events recorded during this period by the muon-trigger ≥ 3. We found 2 candidates (Fig.5) passing our cuts with an expected number of 1.2 events from atmospheric neutrinos as obtained from MC (the samples fulfilling trigger conditions *1, 1-2* and *1-3* contain 131, 17 and 2 events, respectively). Our preliminary estimates for these candidates indicate the probability to be fake events to be equal to $10^{-2} - 10^{-1}$. Therefore we consider them as clear neutrino candidates.

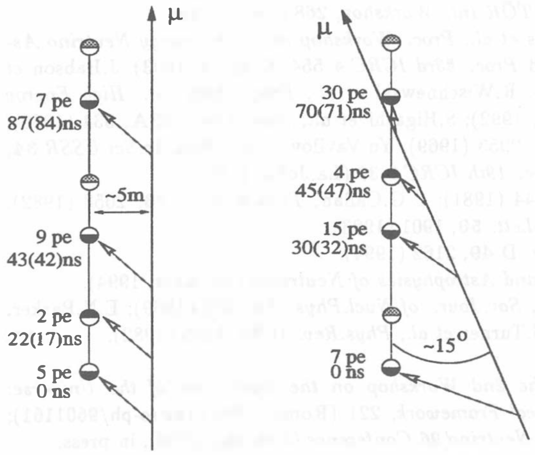

Figure 5: The two neutrino candidates. The hit PMT pairs (channels) are marked by black. Numbers give the measured amplitudes (in photoelectrons) and times with respect to the first hit channel. Times in brackets are those expected for a vertical going upward muon (left) and an upward muon passing the string under 15° (right).

Regarding them as atmospheric neutrino events, an upper limit of $1.3 \cdot 10^{-13}$ muons/cm^2/sec (90 % CL) in a cone with 15 degree half-aperture around the opposite zenith is obtained for muons generated by neutrinos due to neutralino annihilation in the core of the Earth. The limit corresponds to muon energies greater than ≈ 6 GeV. This is still an order of magnitude higher than the limits obtained by Kamiokande [16], Baksan [17] and MACRO [18] but considerable progress is expected from the further analysis of *NT-72, -96* and *-144* data. The *NT-36* effective area of muons fulfilling our cuts is $S = 50$ m^2/string. A rough estimate of the effective area of the full-scale *NT-200* with respect to vertically upward going muons gives $S \approx 400 - 800$ m^2. At the moment the data obtained with *NT-96* array analyzed in a similar way should yield approximately 10 neutrino candidates. This analysis is expected to confirm the method.

5 The Next Steps

On April 6, 1997, a six-string array with 144 optical modules, *NT-144*, was put into operation. By April 30, 1997 it has collected $\approx 2 \cdot 10^7$ muons. We plan to complete the *NT-200* array in April, 1998.

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