The Baikal Deep Underwater Neutrino Experiment: Results, Status, Future *

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We review the present status of the Baikal Underwater Neutrino Experiment and present results obtained with the various stages of the stepwise increasing detector: NT-36 (1993-95), NT-72 (1995-96) and NT-96 (1996-97). Results cover atmospheric muons, first clear neutrino events, search for neutrinos from WIMP annihilation in the center of the Earth, search for magnetic monopoles, and – far from astroparticle physics – limnology.

1 Detector and Site

The Baikal Neutrino Telescope is being deployed in Lake Baikal, Siberia, 3.6 km from shore at a depth of 1.1 km (see fig.1). At this depth, the light absorption length for wavelengths between 470 and 500 nm is about 20 m. Scattering is strongly forward peaked ($\langle \cos \theta \rangle \approx 0.95$). Typical values for the scattering length are about 15 m. Expressed in terms of the effective scattering length $L_{\text{eff}} = L_{\text{scatt}} / (1 - \langle \cos \theta \rangle)$, this corresponds to $L_{\text{eff}} = 300$ m.

NT-200, the medium-term goal of the collaboration [1, 2], will be finished in April 1998 and will consist of 192 optical modules (OMs). An umbrella-like frame carries 8 strings, each with 24 pairwise arranged OMs. Three underwater electrical cables connect the detector with the shore station. Deployment of all detector components is carried out during 5–7 weeks in late winter when the lake is covered by thick ice.

In April 1998, 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-OM 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, $3.2 \times 10^8$ 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 (see fig.2).

The OMs are grouped in pairs along the strings. They contain 37-cm diameter QUASAR PMTs. The two PMTs of a pair are switched in coincidence in order to suppress background from bioluminescence and PMT noise. A pair defines a channel.

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Figure 1: The Baikal detector complex (status since 1994). 1,2 – wire cables to shore, 3 – opto-electrical cable to shore, 4,5,6 – string stations for shore cables 1,2,3, respectively, 7 – string with the telescope, 8 – hydrometric string, 9-14 – ultrasonic emitters.

Figure 2: Schematic view of the Baikal Telescope NT-200. The modules of NT-144, operating since April 1997, are in black. The expansion left-hand shows 2 pairs of optical modules ("svjaska") with the svjaska electronics module, which houses parts of the read-out and control electronics. Top right the array NT-96 is shown, which took data between April 1996 and March 1997.
A muon-trigger is formed by the requirement of \( \geq N \) hits (with hit referring to a channel) within 500 ns. \( N \) is typically set to the value 3 or 4. For such events, amplitude and time of all fired channels are digitized and sent to shore. The event record includes all hits within a time window of \(-1.0 \mu s\) to \(+0.8 \mu s\) with respect to the muon trigger signal. A separate monopole trigger system searches for clusters of sequential hits in individual channels which are characteristic for the passage of slowly moving, bright objects like GUT monopoles.

In the initial project of NT-200, the optical modules were directed alternately upward and downward, with a distance of 7.5 m between pairs looking face to face, and of 5 m between pairs arranged back to back. Due to sedimentation of biomatter deteriorating the sensitivity of upward looking OMs we were forced to direct the OMs of the present arrays essentially downward.

## 2 Track Reconstruction

The parameters of a muon track crossing the detector are determined by minimizing [3]

\[
\chi^2_t = \sum_{i=1}^{N_{hit}} \frac{(T_i(\theta, \phi, u_0, v_0, t_0) - t_i)^2}{\sigma_{ti}^2}
\]  

Here, \( t_i \) are the measured times and \( T_i \) the times expected for a given set of track parameters and simplifying the theoretical picture to that of a "naked" muon not accompanied by electromagnetic showers. \( N_{hit} \) is the number of hit channels, \( \sigma_{ti} \) are the timing errors. A set of parameters defining a straight track is given by \( \theta \) and \( \phi \) – 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.

Only events fulfilling the condition \( \geq 6 \) hits at \( \geq 3 \) strings (trigger 6/3) are selected for the standard track reconstruction procedure which consists of the following steps:

1. A preliminary analysis including several causality criteria which reject events violating the model of a naked muon. After that, a 0-th approximation of \( \theta \) and \( \phi \) is performed.
2. A minimum search (minimization of \( \chi^2_t \)), based on the model of a naked muon.
3. Quality criteria to reject most badly reconstructed events.

The reconstruction procedure is described in detail in [1, 3]. Fig.4 shows a typical single muon event firing 7 of the 18 channels of NT-36 and reconstructed with a \( \chi^2/NDF = 0.57 \) (left), as well as the muon intensity \( I_\mu(\theta) \) as a function of measured zenith angle at the detector depth (right). The angular distribution is well described by MC expectations.

## 3 Separation of Neutrino Events

The canonical signature of neutrino induced events is a muon crossing the detector from below. With the flux of downward muons exceeding that of upward muons from atmospheric neutrino interactions by about 6 orders of magnitude, a careful reconstruction is of prime importance. Clear neutrino signals in the rather small NT-36 could be separated only over a very limited cone around the opposite zenith. Contrary to that, NT-96 can be considered as a real neutrino telescope for a wide region in zenith angle \( \theta \).
3.1 Search for Nearly Upward Moving Neutrinos with NT-36

For separation of nearly vertical upward muons in the NT-36 prototype array we used special separation criteria instead of full reconstruction (see also [5]). These criteria 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 – mostly only along one string. We have chosen the following criteria:

1. $|(t_i - t_j) - (T_i - T_j)| < dt$: the time pattern must be close to that of a straight upward moving muon. $t_i(t_j)$ are the measured times in any hit channels $i(j)$, $T_i(T_j)$ are the “theoretical” times expected for naked, up-going vertical muons and $dt$ is a time cut.

2. $dA_{ij}(\text{down} - \text{up}) > 0.3$: All down-looking channels must see clearly more light than any upward looking channel. $dA_{ij}(\text{down} - \text{up}) = (A_i(\text{down}) - A_j(\text{up}))/A_i(\text{down}) + A_j(\text{up})$ and $A_i(\text{down})/A_j(\text{up})$ are the amplitudes of channel $i(j)$ facing downward (upward).

3. $A_i(\text{down}) > 4pe$: Amplitudes of downward channels must exceed 4 photoelectrons

4. $dA(\text{down} - \text{down}) < 0$. The light must not decrease from bottom to top, as one expects for showers generated by downward muons below the array. $dA(\text{down} - \text{down})$ is defined as that of the 3 possible combinations $dA_{ij}(\text{down} - \text{down}) = (A_i - A_j)/(A_i + A_j)$ of downward channels which has the largest absolute value. For events due to showers below the array it peaks at values close to 1, for vertical neutrino candidates it should be close to zero. The criterium rejects nearly all shower events but only half of the neutrino sample.

We analyzed the data taken with NT-36 between April 8, 1994 and March 5, 1995 (212 days lifetime). There were 6 PMT pairs along each of the 3 strings. The orientation of the channels
from top to bottom at each string was up-down-up-down-up-down. Upward-going muon candidates were selected from a total of $8.33 \cdot 10^7$ events recorded by the muon-trigger "$ \geq 3 \text{ hit channels}". The samples fulfilling trigger conditions 1, 1-2, 1-3 and 1-4 with time cut $dt = 20 \text{ ns}$ contain 131, 17 and 2 events, respectively. Only two events fulfill trigger conditions 1-3 and 1-4. The first is consistent with a nearly vertical upward going muon and the second with an upward going muon with zenith angle $\theta_\mu = 15^\circ$ (fig.4). A detailed analysis [5] yields a fake probability of $\leq 3\%$ for both events.

Figure 4: The two neutrino candidates in NT-36. The hit PMT pairs (channels) are marked in 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).

Considering the two neutrino candidates as atmospheric neutrino events, a 90 \% CL upper limit of $1.3 \cdot 10^{-13}$ (muons cm$^{-2}$ sec$^{-1}$) in a cone with 15 degree half-aperture around the opposite zenith is obtained for upward going muons generated by neutrinos due to neutralino annihilation in the center of the Earth. The limit corresponds to muons with energies greater than the threshold energy $E_{th} \approx 6 \text{ GeV}$, defined by 30m string length. This is still an order of magnitude higher than the limits obtained by Kamiokande [6], Baksan [7] and MACRO [8]. The effective area of NT-36 for nearly vertical upward going muons fulfilling our separation criteria 1-3 with $dt = 20 \text{ ns}$ is $S_{eff} = 50 \text{ m}^2/\text{string}$. A rough estimate of the effective area of the full-scale NT-200 (with eight strings twice as long as those of NT-36) with respect to nearly vertical upward muons gives $S_{eff} \approx 400 - 800 \text{ m}^2$.

3.2 Fully reconstructed neutrinos separated with NT-96

The NT-96 data are analyzed using the standard reconstruction procedure described in sect.2 as well as a method similar to that described in the previous subsection. In this subsection we present results obtained with the standard procedure (see also [4]). For NT-96, the most effective quality cuts are the traditional $\chi^2$ cut, cuts on the probability of non-fired channels not to be hit, and fired channels to be hit ($P_{nonhit}$ and $P_{hit}$, respectively), cuts on the correlation function of measured amplitudes to the amplitudes expected for the reconstructed tracks, and a cut on the amplitude $\chi^2$ defined similar to the time $\chi^2$ defined above. To guarantee a minimum lever arm for track fitting, we reject events with a projection of the most distant channels on the track ($Z_{dist}$) below 35
meters. Due to the small transversal dimensions of NT-96, this cut excludes zenith angles close to the horizon, i.e., the effective area of the detector with respect to atmospheric neutrinos is decreased considerably (fig. 5, left).

The efficiency of all criteria has been tested using MC generated atmospheric muons and upward muons due to atmospheric neutrinos. $1.8 \cdot 10^6$ events from atmospheric muon events (trigger $6/3$) have been simulated, with only 2 of them passing all cuts and being reconstructed as upward going muons. This corresponds to $S/N \approx 1$. Rejecting all events with less than 9 hits, no MC fake event is left, with only a small decrease in neutrino sensitivity. This corresponds to $S/N > 1$ and the lowest curve in fig. 5.

With this procedure, we have reconstructed $5.3 \cdot 10^6$ events taken with NT-96 in April/May 1996. The resulting angular distribution is presented in fig. 5 (right).

![Figure 5](image-url)

**Figure 5:** Left: Effective area for upward muons satisfying trigger $9/3$; solid line – no quality cuts; dashed line – final quality cuts; dotted line – final quality cuts and restriction on $Z_{dist}$ (see text). Right: Experimental angular distribution of events satisfying trigger $9/3$, all final quality cuts and the limit on $Z_{dist}$ (see text).

From the time period between April 16 and May 17, 1996 (18 days lifetime), three neutrino candidates have been separated (see fig. 5, right), in good agreement with the expected number of approximately 2.3. Fig. 6 displays one of the neutrino candidates. Top right the times of the hit channels are shown as a function of the vertical position of the channel. At each string we observe the time dependence characteristically for upward moving particles. The angle regions $\psi_{\text{min}} - \psi_{\text{max}}$ consistent with the observed time differences $\Delta t_{ij}$ between two channels $i, j$ are given by

$$\cos(\psi_{\text{min}} + \eta) < \cos \frac{c \cdot \Delta t_{ij}}{\vec{r}_j - \vec{r}_i} < \cos(\psi_{\text{max}} - \eta)$$

with $\vec{r}_i, \vec{r}_j$ being the coordinates of the channels, $\psi$ the muon angle with respect to $\vec{r}_j - \vec{r}_i$, and $\eta$ the Cherenkov angle. The bottom right picture of fig. 6 shows that the overlap region of all channel combinations of this event clearly lay below horizon.

The same holds for the other two events, one of which is shown in fig. 7a. Fig. 7b, in contrast, shows an ambiguous event giving, apart from the upward solution, also a downward solution. This event is assigned to the downward sample.
Figure 6: A "gold plated" 19-hit neutrino event. Left: Event display. Hit channels are in black. The thick line gives the reconstructed muon path, thin lines pointing to the channels mark the path of the Cherenkov photons as given by the fit to the measured times. The areas of the circles are proportional to the measured amplitudes. Top right: Hit times versus vertical channel positions. Bottom right: The allowed $\theta/\phi$ regions (see text). The fake probability of this event is smaller than 1%.

Figure 7: a) - an unambiguous 14-hit neutrino candidate; b) - an ambiguous event reconstructed as a neutrino event (dashed line) but with a second solution above the horizon (solid line). This event is assigned to the sample of downward going muons.
In the meantime, 70 days from NT-96 have been analyzed, and 12 neutrino candidates have been found. Nine of them have been fully reconstructed, 3 nearly upward vertical tracks hit only 2 strings and give a clear zenith angle but ambiguities in the azimuth angle – similar to the two events from NT-36. Taking into account the degradation of NT-96 due to failed OMs, this is in agreement with MC expectations.

NT-200 will have an effective area of ≈1500 m², after all cuts and averaged over a cone of 60 degrees about the opposite zenith. It will record about one separable neutrino per day.

4 Search for Magnetic Monopoles

GUT monopoles may catalyze processes violating baryon number conservation [9]. For reasonable velocities $\beta \leq 10^{-3}$, a cross section $\sigma_c = 0.17 \cdot \sigma_o / \beta^2$ is predicted for monopole-proton interactions [10], with $\sigma_o$ being of the order of magnitude typical for strong interactions. The distances between sequential proton decays along the monopole track in water can be as short as $10^{-2} - 10^1$ cm.

In order to search for GUT monopoles, a special trigger was implemented which selects events with short-time increase of the counting rate of individual channels, as expected from sequential Cherenkov flashes produced by the proton decay products along a monopole track. During standard data taking runs, the monopole trigger condition was defined as $\geq 3$ hits within a time window of 500 μsec in any of the channels.

The data taken from April 16th to November 15th 1993 with NT-36 were used to search for monopole candidates. We requested that one channel had counted $\geq 7$ hits and the second channel looking to its face and located 7.5 m away along the string $\geq 3$ hits during the same 500 μsec. This reduces the number of the experimentally observed candidates from $3.5 \cdot 10^7$ to zero. From the non-observation of monopole candidates we obtain the upper flux limits (90 % CL) shown in Fig. 8 together with our earlier results, limits from IMB [11] and Kamiokande [12] and with the astrophysical Parker limit. Limits of $10^{-15}$ and $2.7 \cdot 10^{-16}$ cm$^{-2}$ s$^{-1}$ have been obtained by the MACRO [14] and Baksan [13] experiments, respectively. With the whole statistics taken since 1993, the minimal detectable flux can be lowered by more than an order of magnitude.

![Figure 8: Upper limits (90 % CL) on the flux of magnetic GUT monopoles as a function of their velocity $\beta$, for different catalysis cross sections $\sigma_o$.](image)
Apart from GUT monopoles catalyzing baryon decay, relativistic monopoles may be detected as well. The large magnetic charge of a monopole \( g_o = 68.5e \) results in a giant Cherenkov radiation, equal to that of a 14-GeV muon for a monopole with \( \beta_{mon} \approx 1 \). The non-stochastic nature of the Cherenkov emission by relativistic monopoles (contrary to a 14 GeV muon!) may be used to select monopole candidates. Actually, even monopoles with velocities below their Cherenkov threshold \( (\beta_{mon} \approx 0.75) \) may be detected, namely by Cherenkov radiation of \( \delta \)-electrons (down to \( \beta_{mon} \approx 0.6 \)). The effective area of NT-200 for monopoles with \( \beta \approx 1 \) is estimated as \( 20,000 \text{ m}^2 \).

5 Limnology

Apart from its function as a neutrino telescope, the Baikal detector can be used to monitor water parameters. The array permanently records photomultiplier counting rates, and periodically parameters like optical transmission at various wavelengths, temperature, conductivity, pressure (CDT sondes), and speed of sound. These measurements form a unique data set which can be related to CDT measurements at other locations in order to build a comprehensive picture of water exchange processes in the lake.

For reasons of illustration, we show below counting rate variations at various time scales recorded with NT-36 in 1993/94. Counting rates of single PMTs as well as the ”local trigger rates” (coincidence rates of the 2 PMTs of a pair) are dominated by water luminescence.

![Figure 9: Average counting rate of OMs vs. time, compared to bacteria concentration at surface.](image-url)

Fig. 9 gives the counting rate over 2 years and compares it to the bacteria concentration measured at a distance of 50 km to the NT-200 site, at 10 m depth below surface. In August/September we observe an increase of the luminosity to extremely high levels. The changes of the local trigger rate are not reflected in the muon trigger rate, since the muon trigger is essentially dominated by atmospheric muons, with negligible contribution by random hits (water luminescence or dark noise). This is demonstrated in fig.10 on a shorter time scale, for a time interval of marked changes of the local trigger rate following a strong storm at August 3rd, 1993, which had washed a lot of water from a nearby river to the lake.

Fig.11 shows a short period of about 8 hours when the counting rates sequentially increased, starting with the highest OMs and ending with the lowest. From the time shift of the 3 curves a vertical
current of $2.3 \text{ cm sec}^{-1}$ is deduced. This is noticeable since the vertical speed of water currents in spring, when the vertical water renewal is considered to be most intensively, is only $0.2-0.3 \text{ cm sec}^{-1}!$

![Diagram](image1.png)

Figure 10: a) Local trigger rates for channel 7 (downward facing) and channel 8 (upward facing) for August 1st-9th, 1993. The counting rates are averaged over 30 min. b) Muon trigger rates (condition 4/1) for channel 7 and 8. Counting rates are averaged over 50 min.

![Diagram](image2.png)

Figure 11: Counting rate of three OMs along one string during an 8 hour interval at Sept. 24, 1993.

6 Conclusions and Outlook

The Baikal detector is well understood, and first atmospheric neutrinos have been identified. Their total number agrees well with Monte Carlo expectations. Furthermore, limits on the flux of GUT magnetic monopoles have been derived. The detector has the potential to study so different questions like the search for neutrinos from WIMP annihilation in the center of the Earth on the one hand, and monitoring of deep water ventilation processes on the other hand.
The Baikal site is competitive to Oceans: The stronger absorption may be taken into account by a somewhat denser spacing which, on the other hand, might be a natural approach if one focuses to lower thresholds than in Oceans. The external noise is of similar magnitude like in Oceans, but with strong seasonal variations. The smaller depth has been shown to be no serious drawback, since with appropriate methods neutrinos can be separated effectively. The most remarkable advantage of the site is the ice cover which allows reliable and inexpensive deployment and retrieval - still an practically unsolved problem in the case of Ocean projects.

After 144 Optical Modules have been deployed in March/April 1997, the NT-200 detector will be completed in April 1998.

In the following years, NT-200 will be operated as a neutrino telescope with an effective area between 1000 and 5000 m² typically, depending on the energy. This corresponds, after all cuts, to about 1 atmospheric neutrino per day. Presumably still too small to detect neutrinos from AGN and other extraterrestrial sources, NT-200 can be used to push the flux limits for neutrinos from WIMP annihilation and for magnetic monopoles. It will also be a unique environmental laboratory to study water processes in Lake Baikal.

Apart from its own value, NT-200 is regarded to be a prototype for a telescope 20-50 times larger. With 2000 OMs, a threshold of 10-20 GeV and an effective area of 50,000 to 100,000 m², this telescope would have a realistic detection potential for extraterrestrial sources of high energy neutrinos. With its comparatively low threshold, it would fill a gap between underground detectors and planned high threshold detectors of cube kilometer size.

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References
