The BAIKAL neutrino project: status report

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We review the present status of the Baikal Neutrino Project and present preliminary results of a search for upward going atmospheric neutrinos, WIMPs and magnetic monopoles obtained with the detector NT-200 during 1998. Also the results of a search for very high energy neutrinos with partially completed detector in 1996 are presented.

1. Detector and Site

The Baikal Neutrino Telescope is deployed in Lake Baikal, Siberia, 3.6 km from shore at a depth of 1.1 km. *NT-200*, the medium-term goal of the collaboration [1], was put into operation at April 6th, 1998 and consists of 192 optical modules (OMs). An umbrella-like frame carries 8 strings, each with 24 pairwise arranged OMs. Three underwater electrical cables and one optical cable connect the detector with the shore station.

The OMs are grouped in pairs along the strings. They contain 37-cm diameter QUASAR - photo multipliers (PMs) which have been developed specially for our project [2,3]. The two PMs of a pair are switched in coincidence in order to suppress background from bioluminescence and PM noise. A pair defines a *channel*.

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 3 or 4. For such events, amplitude and time of all fired channels are digitized and sent to shore. 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.

Here we present preliminary results of analysis of data, which were accumulated in the first 234 live days of NT-200 as well as results obtained from the analysis of data taken with NT-96, the 1996 stage of the detector.

2. Separation of fully reconstructed neutrino events

The signature of neutrino induced events is a muon crossing the detector from below. The reconstruction algorithm is based on the assumption that the light radiated by the muons is emitted under the Cherenkov angle with respect to the muon path. We don't take into account light scattering because the characteristic distances for atmospheric neutrino induced muons detection do not exceed 1÷2 scattering lengths of light in Baikal water (mean scattering angle cosine ≈ 0.88)[1].

The algorithm uses a single muon model to reconstruct events. We apply procedure rejecting hits, which are very likely due to dark current or water luminosity as well as hits which are due to showers and have large time delays with respect to expected hit times from the single muon Cherenkov light.

Determination of the muon trajectory is based on the minimization of a χ^2 function with respect to measured and calculated times of hit channels. As a result of the χ^2 minimization we obtain the track parameters (θ , ϕ and spatial coordinates).

The reconstruction yields a fraction of about $4.6 \cdot 10^{-2}$ of events which are reconstructed as upward going with respect to whole event sample fulfilling the trigger condition $\geq 6/3$ (at least 6 hits on at list 3 strings). That is still far from a suppression factor 10^{-6} necessary for the depth of NT-200. To reject most of the wrongly reconstructed events we use the set of quality criteria. If the event doesn't obey any of chosen criteria, it is rejected as wrongly reconstructed. Different to NT-96 [4], the neutrino selection algorithm for NT-200 operates with trigger $\geq 7/3$.

For NT-200 neutrino search, the following cuts are most effective: (1) a traditional χ_t^2 cut; (2) the minimum track length in the array; (3) the probability of non-fired channels not to be hit and fired channels to be hit; (4) the correlation of measured amplitudes to the amplitudes expected for reconstructed track; (5) an amplitude χ_a^2 defined similar to the time χ_t^2 ; (6) the correlation between measured hit times and vertical distances of channels in array (see eq.1 below). The efficiency of the procedure and correctness of the MC background estimation have been tested with a sample of $2.8 \cdot 10^6$ MC-generated atmospheric muons and with MC-generated upward going muons due to atmospheric neutrinos. None of MC background events has passed all

Table 1

The fraction of events passing cuts for experimental and MC background sample.

Applying	exper.	MC backgr.
cuts	sample	sample
$\theta > 90^o$	$4.9 \cdot 10^{-2}$	$4.6 \cdot 10^{-2}$
+ "soft" cut(2)	$2.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$
+ "soft" cut(4)	$1.1 \cdot 10^{-2}$	$1.1 \cdot 10^{-2}$
+ "soft" cut(3)	$5.4 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$

cuts. Unfortunately, the restricted statistics of the MC background sample does not allow us to compare the behavior of MC background and experimental samples at all levels of tracks rejection. To demonstrate the principal agreement between the action of the cuts to experimental and and MC samples, we show in Table 1 the fraction of events passing cuts on the same variables but with softer cut values.

Data taken with NT-200 between 1998 April and 1999 February cover 234 days life time. For this period we got $5.3 \cdot 10^7$ events with trigger $\geq 6/3$. The set of above criteria was applied to this sample yielding 35 events which pass all of them. This number is in good agreement with 31 events expected from neutrino induced muons for this period. The reconstructed angular distribution for upward going muons from the experimental sample after all cuts is shown in Fig.1. In the same figure the MC expected angular distribution for muons from neutrinos is presented.

3. Identification of nearly vertically upward moving muons

The search for weakly interacting massive particles (WIMPs) with the Baikal neutrino telescope is based on the search for a statistically significant excess of neutrino induced nearly vertically upward going muons with respect to the



Figure 1. Experimental angular distribution of reconstructed upward going muons in *NT-200*. Filled histogram - MC expected distribution.

expectation for atmospheric neutrinos.

Different to the standard analysis which has been described in the previous section, the method of event selection relies on the application of a series of cuts which are tailored to the response of the telescope to nearly vertically upward moving muons [4–6]. The cuts remove muon events far away from the opposite zenith as well as background events which are mostly due to pair and bremsstrahlung showers below the array and to bare downward moving atmospheric muons with zenith angles close to the horizon $(\theta > 60^{\circ})$. The candidates identified by the cuts are afterwards fitted in order to determine their zenith angles.

For the present analysis we included all events with ≥ 6 hit channels, out of which ≥ 4 hits are along at least one of all hit strings. To this sample, a series of 6 cuts is applied. Firstly, the time differences of hit channels along each individual string have to be compatible with a particle close to the opposite zenith (1). The event length should be large enough (2), the maximum recorded amplitude should not exceed a certain value (3) and amplitude of each upward looking



Figure 2. Zenith angular distribution of nearly vertically upward neutrino candidates as well as MC expectation for atmospheric neutrinoinduced muons (histogram).

hit channel has to be smaller then a certain value (4). The center of gravity of hit channels should not be close to the detector bottom (5). The latter two cuts reject efficiently brems showers from downward muons. Finally, also time differences of hits along *different* strings have to correspond to a nearly vertical muon (6).

The effective area of the full scale neutrino telescope NT-200 for muons with energy E>10 GeV, which move close to opposite zenith and fulfill all cuts, exceeds 2500 m².

Table 2

90% c.l. upper limits on the muon flux from the center of the Earth for six regions of zenith angles obtained in Baikal experiment

c		_		
l	Cone	Data	Back-	Flux Limit
l			ground	$(E_{\mu} > 10 GeV)$
l			events	$(cm^{-2}s^{-1})$
l	30°	12	11.1	5.6×10^{-14}
ſ	25°	9	9.1	4.0×10^{-14}
Γ	20°	7	7.2	2.9×10^{-14}
ſ	15°	4	4.4	2.0×10^{-14}
	10°	2	1.5	2.4×10^{-14}
ĺ	5°	1	0.5	1.7×10^{-14}

From 234 days of effective data taking 32957

events survive cut (1).

After applying all cuts, ten events were selected as neutrino candidates, compared to 8.9 expected from atmospheric neutrinos. The zenith angular distribution of these ten neutrino candidates is shown in fig.2.

Regarding the ten detected events as being due to atmospheric neutrinos, one can derive an upper limit on the flux of muons from the center of the Earth due to annihilation of neutralinos - the favored candidate for cold dark matter.

The combined numbers of observed and expected background events and the 90% c.l. muon flux limits for six cones around the nadir obtained with the Baikal neutrino telescopes NT-96 [4] and NT-200 (1998) are shown in Table 2.

The comparison of Baikal flux limits with those obtained by Baksan [7], MACRO [8], Kamiokande [9] and Super-Kamiokande [10] is shown in fig.3.



Figure 3. Comparison of Baikal nearly vertically upward muon flux limits with those from other experiments.

4. Search for fast monopoles ($\beta > 0.75$)

Fast bare monopoles with unit magnetic Dirac charge and velocities greater than the Cherenkov threshold in water ($\beta = v/c > 0.75$) are promising survey objects for underwater neutrino telescopes. For a given velocity β the monopole Cherenkov radiation exceeds that of a relativistic muon by a factor $(gn/e)^2 = 8.3 \cdot 10^3$ (n = 1.33)- index of refraction for water) [11,12]. Therefore fast monopoles with $\beta \ge 0.8$ can be detected up to distances 55 m \div 85 m corresponding to effective areas of $(1\div 3)\cdot 10^4$ m².

The natural way to search for fast monopoles is based on the selection of events with high multiplicity of hits and high amplitudes. In order to reduce the background from downward atmospheric muons and especially atmospheric muon bundles we restrict ourself to monopoles coming from the lower hemisphere.

In the present analysis of the first 234 live days data of NT-200, the following cuts have been applied to the detected events.

- Number of hit channels $N_{hit} > 35$
- The value of space-time correlation

$$cor_{zt} = \frac{1}{N_{hit}} \sum_{i=1}^{N_{hit}} \frac{(z_i - \bar{z})(t_i - \bar{t})}{\sigma_z \sigma_t} > 0.6, (1)$$

where z_i and t_i are z-coordinate and time of hit channels, \bar{z} , \bar{t} , σ_z and σ_t - their average values and standard deviations.

- At least two of all hit channels have the amplitudes more than 400 ph.el.
- The time differences of hit channels Δt_{ij} fulfill the following condition:

$$max(\Delta t_{ij} - \frac{R_{ij}}{v}) < 50 \text{ns}, \tag{2}$$

where R_{ij} and v - range between two hit channels and light velocity in the water, respectively.

There are no events which survive all cuts. Using the MC calculated acceptance of NT-200, a 90% c.l. upper limit on the monopole flux has been obtained.

The combined upper limit for an isotropic flux of bare fast magnetic monopoles obtained with *NT-36*, *NT-96* [13] and *NT-200* as well as limits from underground experiments MACRO, Soudan2, KGF, Ohya and AMANDA [14–18] are shown in Fig.4.



Figure 4. Upper limits on the flux of fast monopoles obtained in different experiments.

5. The limit on the diffuse neutrino flux

In this section we present results of a search for neutrinos with $E_{\nu} > 10$ TeV obtained with *NT-96* [19].

The used search strategy for high energy neutrinos relies on the detection of the Cherenkov light emitted by the electro-magnetic and (or) hadronic particle cascades and high energy muons produced at the neutrino interaction vertex in a large volume around the neutrino telescope.

Within the 70 days of effective data taking of NT-96, $8.4 \cdot 10^7$ events with $N_{hit} \ge 4$ have been selected.

For this analysis we used events with ≥ 4 hits along at least one of all hit strings. The time difference between any two channels on the same string was required to obey the condition:

$$|(t_i - t_j) - z_{ij}/c| < a \cdot z_{ij} + 2\delta, \ (i < j).$$
 (3)

The t_i, t_j are the arrival times at channels i, j, and z_{ij} is their vertical distance. $\delta = 5$ ns accounts for the timing error and a = 1 ns/m.

8608 events survive the selection criterion (3). The highest multiplicity of hit channels (one event) is $N_{hit} = 24$.

Since no events with $N_{hit} > 24$ are found in our data we can derive an upper limit on the flux of

high energy neutrinos which produce events with multiplicity $N_{hit} > 25$.

The shape of the neutrino spectrum was assumed to behave like E^{-2} as typically expected for Fermi acceleration. In this case, 90% of expected events would be produced by neutrinos from the energy range $10^4 \div 10^7$ GeV. Comparing the calculated rates with the upper limit to the number of zero events with $N_{hit} > 24$, we obtain the following 90% c.l. upper limit to the diffuse neutrino flux:

$$\frac{d\Phi_{\nu}}{dE}E^2 < 1.4 \cdot 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}.$$
 (4)



Figure 5. Upper limits on the differential flux of high energy neutrinos obtained by different experiments as well as upper bounds for neutrino fluxes from a number of different models. The triangle denotes the FREJUS limit.

Fig.5 shows the upper limits on the diffuse high energy neutrino fluxes obtained by Baikal (this work), SPS-DUMAND [20], AMANDA-A [21], EAS-TOP [22] and FREJUS [23] (triangle) as well as a model independent upper limit obtained by V.Berezinsky [24] (curve labeled B) (starting from the energy density of the diffuse X- and gamma-radiation $\omega_x \leq 2 \cdot 10^{-6}$ eV cm⁻³ as follows from EGRET data [25]) and the atmospheric neutrino fluxes [26] from horizontal and vertical directions (upper and lower curves, respectively). Also shown are predictions from Stecker and Salamon model [27] (curve labeled SS) and Protheroe model [28] (curve labeled P) for diffuse neutrino fluxes from quasar cores and blazar jets.

We expect that the analysis of data taken with NT-200 (1998) would allow us to lower this limit down to $(2\div 4)\cdot 10^{-6}$ cm⁻²s⁻¹sr⁻¹GeV.

6. EAS array and acoustic signal measurements

Since March 1998 we have performed measurements of EAS with a Cherenkov array deployed on the ice cover just above *NT-200* [29].

In March/April 2000 we continue the experiments with the EAS array. It consists of 4 upward facing QUASAR PMs placed in special containers. Three of them were located at the corners and one in the center of an equilateral triangle. The distance between the central and each of the outer detectors was 100 m. The array was operating in 2 modes: a Cherenkov light detecting mode and a scintillator mode. For the Cherenkov mode conic reflectors were put on the containers to increase the effective area of PMs. For the scintillator mode reflectors were replaced by 0.25 m² scintillator plates.

In the Cherenkov mode, the EAS array operated in coincidence with NT-200 for studying the angular resolution of the latter. The energy threshold in this case was about 200 TeV. The preliminary analysis of data collected during 1999 shows that the angular resolution of NT-200(without applying any cuts, which usually used to reject badly reconstructed tracks) is better than 5 degrees.

In the scintillator mode, the EAS array has been used as a trigger system in a search for acoustic signals from EAS. The core of EAS triggered the scintillater array is expected to lead to an acoustic signal in the ice and in the upper water layer. With 5 PeV energy threshold of the EAS-array, 2-3 events per hour have been observed. Acoustic hydrophone was placed 90 m apart from the center of the EAS array at a depth 5 m. Characteristic bipolar acoustic signals with about 150 μ s duration and with a rea-

sonable delay time compared to the EAS trigger have been detected. A preliminary analysis of the data shows that the amplitudes of the acoustic signals are somewhat larger than it would be expected from standard thermoacoustic theory [30]. The source of this disagreement may be a rough calibration of hydrophon. We plan to continue the investigation of acoustic signals from EAS in the next year.

7. Conclusions and Outlook

The deep underwater neutrino telescope NT-200 in Lake Baikal is taking data since April 1998. Using the first 234 live days, 35 neutrino induced upward muons have been reconstructed. Although in a good agreement with MC expectation this number is on factor 3 lower then predicted for the fully operational NT-200. The reason is that, due to unstable operation of electronics, in average only 50 - 70 channels have taken data during 1998. This is in contrast to 1999 and 2000 data taking where stability had improved. Ten events within a 30 degree half angle cone around nadir have been selected and limits on the excess of muon flux due to WIMP annihilation in the center of the Earth have been derived. Also a new limit on the flux of fast monopoles has been obtained.

In the following years, NT-200 will be operated as a neutrino telescope with an effective area between 1000 and 5000 m², depending on the energy. It will investigate atmospheric neutrino spectra above 10 GeV (about 1 atmospheric neutrino per two-three days). Due to the high water transparency and low light scattering with effective scattering length greater than 150m÷200m, the effective volume of NT-200 for high energy electron and tau neutrinos detection is more than two orders of magnitude larger than its geometrical volume. This will permit a search for diffuse neutrino fluxes from AGN and other extraterrestrial sources on a level of theoretical predictions.

With an effective area two times larger than Super-Kamiokande, for nearly vertically upward muons ($E_{\mu} > 10$ GeV) *NT-200* will be one of the most powerful arrays for indirect search for WIMP annihilation in the center of the Earth during the next few years. It will also be a unique environmental laboratory to study water processes in Lake Baikal.

Apart from its own goals, NT-200 is regarded to be a prototype for the development a telescope of next generation with an effective area of 50,000 to 100,000 m². The basic design of such a detector is under discussion at present.

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