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THE LAKE BAIKAL NEUTRINO EXPERIMENT: PRESENT AND FUTURE

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We review the present status and future of the Lake Baikal Neutrino Experiment. Selected physics results concerning a search for upward-going atmospheric neutrinos, WIMPs and relativistic magnetic monopoles are presented.

Представлены современное состояние и перспективы байкальского нейтринного эксперимента. Представлены некоторые результаты по поиску восходящих нейтринных событий, слабо взаимодействующих массивных частиц и релятивистских магнитных монополей.

INTRODUCTION

The Lake Baikal Neutrino experiment has nearly 20 years history, from small short experiments with a few PMTs in the early 80s to the present large-scale long-term operating neutrino telescope NT-200 [1, 4], which was put into full operation on 6 April 1998. The telescope's effective area for muons is 2000–10000 m^2, corresponding to a muon energy. The expected rate of muons from atmospheric neutrinos, with a muon energy threshold of 10 GeV and after all cuts rejecting background, is about 1 per two days.

1. DETECTOR AND SITE

The Neutrino Telescope NT-200 is located in the southern part of Lake Baikal at 3.6 km from the shore and at a depth of about 1 km. The absorption length $L_{\rm abs}$ of water at the site for wavelengths between 470 and 500 nm is about 20 m and seasonal variations are less than 20 %. The light scattering is subjected strongly to seasonal variations and those from year to year. We can say now that light scattering is rather strongly anisotropic and typical values of $L_{\rm scatt}$ are about 15–20 m. NT-200 consists of 192 optical modules (OMs) at 8 strings arranged at an umbrella-like frame [1]. Pairs of OMs are switched in coincidence with 15 ns time window and define a channel. We pursue pairwise ideology for many reasons: to suppress individual OM background counting rates due to OM dark current and water luminescence, the level of late- and afterpulses, etc. Four OMs form a «sviazka». The OM [2] consists of QUASAR-370 phototube [5, 6] enclosed in transparent, nearly spherical

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pressure housing. The optical contact between the photocathode region of the phototube and the pressure glass sphere is made by liquid glycerine sealed with a layer of polyurethane. Apart from the phototube, every OM contains two HV power supplies (25 and 2 kV), a voltage divider, two preamplifiers, a calibration LED and a vacuum probe. The QUASAR-370 phototube has been developed specially for the Lake Baikal Neutrino Experiment by INR and KATOD Company in Novosibirsk. The phototube is a hybrid one and has excellent time and single electron resolutions.

The detector electronics system [1] is hierarchical: from the lowest level to the highest one — OM's electronics, «sviazka» electronics module, string electronics module and the detector electronics module, where detector trigger signals are formed and all information from the string electronics module is received and sent to the shore station. Three underwater electrical cables connect the detector with the shore station. The detector is operated from the shore station.

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, the 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 do not take into account light scattering because the characteristic distances for atmospheric neutrino-induced muon detection do not exceed $1 \div 2$ scattering lengths of light in the 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 does not 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 $\geq 7/3$.

Table 1. **The fraction of events passing cuts for experimental and MC background sample**

Applied cuts	Exper. sample	MC backgr. sample
$\theta > 90°$	$4.9 \cdot 10^{-2}$	$4.6 \cdot 10^{-2}$
+ «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)	$5.4 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$

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 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 track rejection. To demonstrate the principal agreement between the action of the cuts to experimental and MC samples, we show in Table 1 the fraction of events passing cuts on the same variables but with softer cut values.

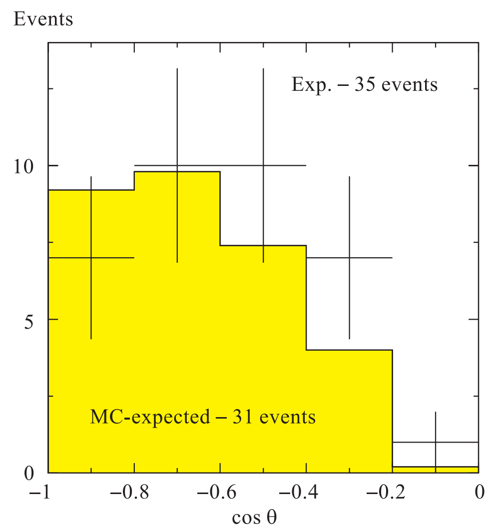

Fig. 1. Experimental angular distribution of reconstructed upward-going muons in NT-200. Filled histogram — MC-expected distribution

Data taken with NT-200 between April 1998 and February 1999 cover 234 days' lifetime. For this period we got $5.3 \cdot 10^7$ events with trigger $\geq 6/3$. The set of the 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 expectation for atmospheric neutrinos.

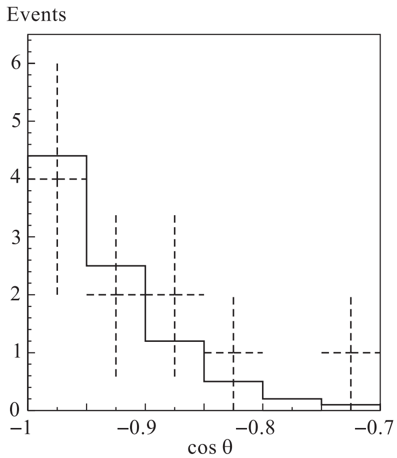

Fig. 2. Zenith angular distribution of nearly vertically upward neutrino candidates as well as MC expectation for atmospheric neutrino-induced muons (histogram)

Different from 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, 7, 8]. 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 ($\theta > 60°$). 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 the amplitude of each upward-looking hit channel has to be smaller than 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 2,500 m^2. From 234 days of effective data taking, 32,957 events survive cut (1).

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 the Baikal experiment**

Cone	Data	Background events	Flux limit ($E_\mu > 10$ GeV), $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$
30°	12	11.1	$5.6\cdot10^{-14}$
25°	9	9.1	$4.0\cdot10^{-14}$
20°	7	7.2	$2.9\cdot10^{-14}$
15°	4	4.4	$2.0\cdot10^{-14}$
10°	2	1.5	$2.4\cdot10^{-14}$
5°	1	0.5	$1.7\cdot10^{-14}$

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 the Baikal flux limits with those obtained by Baksan [9], MACRO [10], Kamiokande [11] and Super-Kamiokande [12] is shown in Fig. 3.

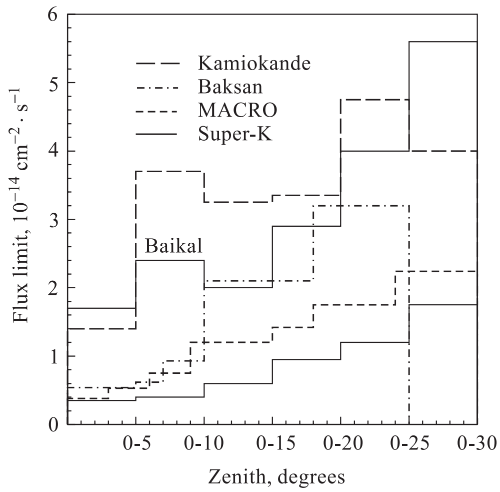

Fig. 3. Comparison of the Baikal nearly vertically upward muon flux limits with those from other experiments

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) [13, 14]. Therefore fast monopoles with $\beta \geq 0.8$ can be detected up to distances $55 \div 85$ m, corresponding to effective areas of $(1 \div 3) \cdot 10^4$ m^2.

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 ourselves to monopoles coming from the lower hemisphere.

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

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

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

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

- At least two of all hit channels have the amplitudes more than 400 ph.el.

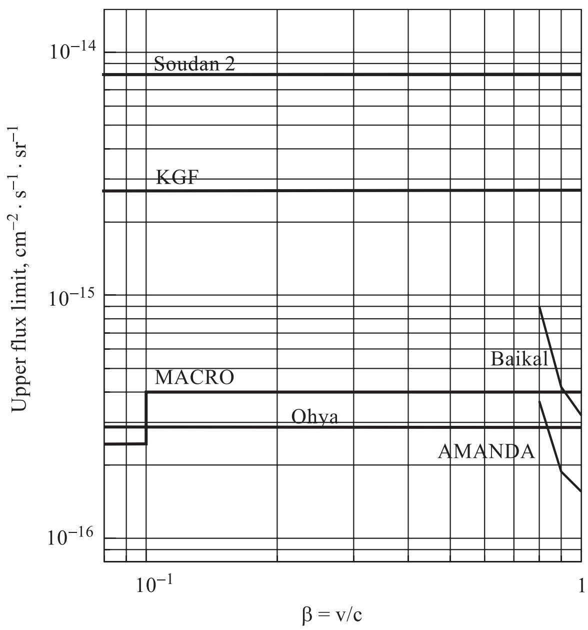

Fig. 4. Upper limits on the flux of fast monopoles obtained in different experiments

- The time differences of hit channels Δt_{ij} fulfill the following condition:

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

where R_{ij} and v are the 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 [15] and NT-200 as well as limits from underground experiments MACRO, Soudan 2, KGF, Ohya and AMANDA [16–20] are shown in Fig. 4.

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 [21]. 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 $N_{\text{hit}} \geq 4$ have been selected. For this analysis we used events with $\geq$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

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

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 $N_{\rm hit} = 24$. Since no events with $N_{\rm hit} > 24$ are found in our data, we can derive an upper limit on the flux of high-energy neutrinos which produce events with multiplicity $N_{\rm hit} > 25$. 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 $N_{\rm hit} > 24$, we obtain the following 90 % C.L. upper limit to the diffuse neutrino flux:

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

Figure 5 shows the upper limits on the diffuse high-energy neutrino fluxes obtained by Baikal (this work), SPS-DUMAND [22], AMANDA-A [23], EAS-TOP [24] and FREJUS [25] (triangle) as well as a model-independent upper limit obtained by V.Berezinsky [26] (curve labeled B) (starting from the energy density of the diffuse X- and gamma-radiation $\omega_x \leq 2 \cdot 10^{-6}$ eV $\cdot$ cm^{-3} as follows from EGRET data [27]) and the atmospheric neutrino fluxes [28] from horizontal and vertical directions (upper and lower curves, respectively). Also shown are predictions from Stecker and Salamon model [29] (curve labeled SS) and Protheroe model [30] (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 $(2 \div 4) \times 10^{-6}$ GeV $\cdot$ cm^{-2} $\cdot$ s^{-1} $\cdot$ sr^{-1}.

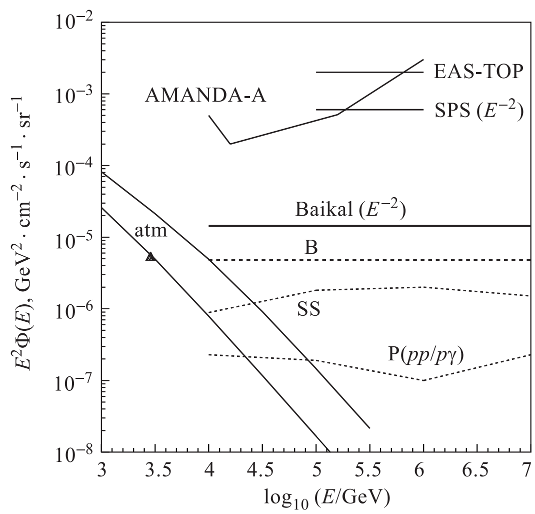

Fig. 5. Upper limits on the differential flux of high-energy neutrinos obtained by different experiments as well as upper bounds for neutrino fluxes from a number of different models. The triangle denotes the FREJUS limit

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 [31].

In March–April 2000 we continued the experiments with the EAS array. It consists of 4 upward-facing QUASAR-370G phototubes placed in special containers. QUASAR-370G is a slightly modified version of the QUASAR-370 phototube to withstand high mean anode current due to night sky light background. 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 two modes: a Cherenkov light-detecting mode and a scintillator mode. For the Cherenkov mode, Winston cones are used to increase the effective area of phototubes. For the scintillator mode, Winston cones are replaced by 0.25 m^2 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 are 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 which triggered the scintillator 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 of 5 m. Characteristic bipolar acoustic signals with about 150 μs duration and with a reasonable 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 would be expected from standard thermoacoustic theory [32]. The source of this disagreement may be a rough calibration of hydrophone. We are planning to continue studying acoustic signals from the EAS core next year.

CONCLUSIONS AND OUTLOOK

The deep underwater neutrino telescope NT-200 in Lake Baikal has been 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 by a factor of 3 lower than predicted for the fully operational NT-200. The reason is that, due to unstable operation of electronics, on average only 50–70 channels took 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 m^2, 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 $150 \div 200$ m, the effective volume of NT-200 for high-energy electron and tau neutrino 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 that of 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 as a prototype for the development of a telescope of next generation with an effective area of 50,000 to 100,000 m^2. The basic design of such a detector is under discussion at present.

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