Status of the Baikal experiment

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Abstract

We review the status of the Lake Baikal Neutrino Experiment. The Neutrino Telescope NT200 is operating since 1998 and has been upgraded to the 10 Mton detector NT200+ in 2005. We present selected results from long-term operation of NT200, including an improved limit on a diffusive astrophysical neutrino flux. Preparation towards a km3-scale (Gigaton volume) detector in Lake Baikal is a currently central activity. As an important milestone, a km3-prototype string, based on completely new technology, has been installed and is operating together with NT200+ since April, 2008.

1 Introduction

The Baikal Neutrino Telescope NT200 is taking data since 1998. Since 2005, the upgraded 10-Mton scale detector NT200+ is in operation. Detector configuration and performance have been described elsewhere [1, 2, 3, 4, 5, 6]. The most recent milestone of the ongoing km3-telescope research and development work (R&D) was the installation of a "new technology" prototype string in spring 2008, operating now as part of NT200+. Fig.1 gives a sketch of the current status of the telescope NT200+, including the km3-prototype string.

In this paper we review astroparticle physics results obtained with NT200, in particular an improved limit on a diffusive astrophysical neutrino flux, and discuss the R&D activities towards a km3-scale Baikal telescope. Results of a feasiblity study for acoustic detection of UHE-energy neutrinos and of associated science activities (e.g. site studies, limnology) have been discussed elsewhere [7].

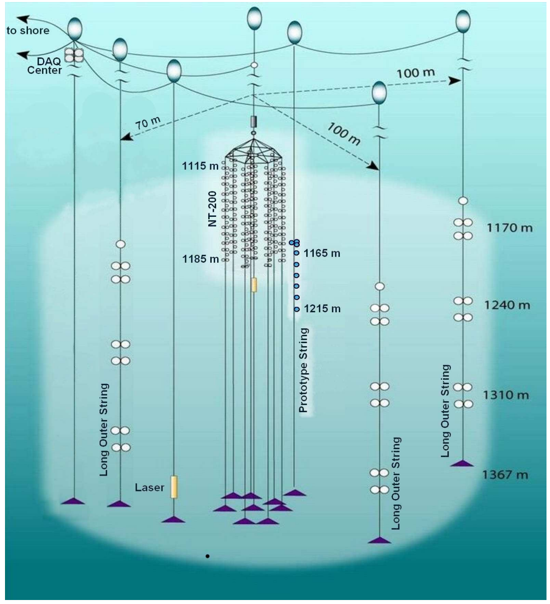

Figure 1: The Baikal Telescope NT200+ as of 2008: the compact NT200 (center), 3 long outer strings and the new technology km3-prototype string.

2 Selected physics results from NT200

2.1 Atmospheric neutrinos

The signature of charged current muon neutrino events is a muon crossing the detector from below. Muon track reconstruction algorithms and background rejection have been described elsewhere [8]. Compared to [8], the analysis of the 5-year sample (April 1998 – February 2003, 1008 days live time) was optimized for higher signal passing rate, i.e. accepting a slightly higher contamination of $\sim$20% fake events [9]. A total of 372 upward going neutrino candidates were selected. From Monte-Carlo simulation a total of 385 atmospheric neutrino and background events are expected, with a median muon-angular resolution of 2.2^o. The skyplot for this event sample is shown in Fig.2.

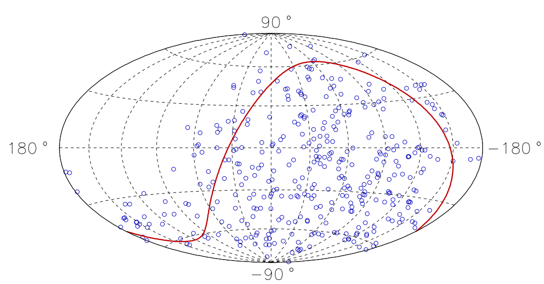

Figure 2: Skyplot (galactic coordinates) of neutrino events for five years. The solid curve shows the equator.

For the ν_μ-analysis procedure, a standard 3-dimensional muon reconstruction is performed for all events [8]. The good agreement of the obtained downward muon angular distribution with MC is shown in Fig.3(right) (see also earlier Baikal flux measurements [1]). All events reconstructed as upgoing are treated in a second pass as neutrino candidates, to additionally filter out fake events. The zenith-angular distribution of upward reconstructed neutrino events is given in Fig.3(left), for two different choices of the background content (S/N$\sim$3 and $\sim$10, respectively), as used for different analyses. In Fig.3 also shown are MC predictions for the sum of ν-signal and background without and with ν-oscillations (see Sect.2.2 for parameters), as well as for the background (histograms from top to bottom, respectively). Data and MC are in good agreement, given the known systematic uncertainties of absolute atmospheric ν-flux predictions.

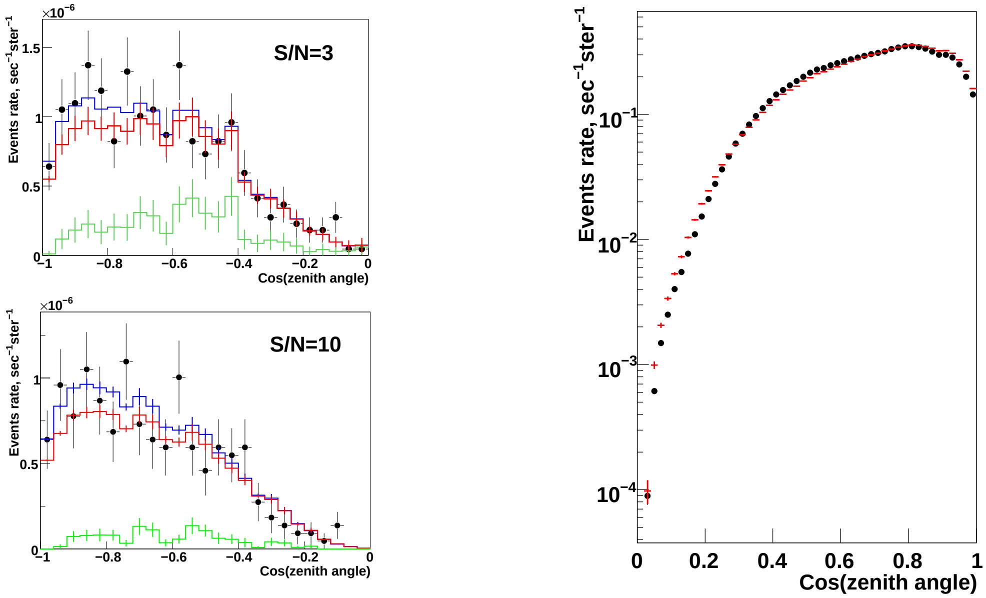

Figure 3: Distribution of cos(zenith) for muon events. Left: neutrino event samples (data - symbols, MC - histograms (from top): sig+bkg for non-osc., oscillation and bkg); Right: downward atmopsheric muons (data - symbols, MC - histogram).

2.2 Search for Neutrinos from WIMP Annihilation

The search for WIMPs annihilating in the Earth center with the Baikal neutrino telescope is based on a possible signal of nearly vertically upward going muons, exceeding the flux of atmospheric neutrinos. Signal event selection relies on a series of cuts which are tailored to the response of the telescope to nearly vertically upward moving muons [10]. These cuts select muons with $-1 < \cos(\theta) < -0.75$ and result in a detection area of about 1800 m^2 for vertically upward going muons. The energy threshold for this analysis is $E_{\text{thr}} \sim 10$ GeV, i.e. lower then for the standard ν_μ-analysis described in Sect.2.1 ($E_{\text{thr}} \sim 15 - 20$ GeV).

From 1038 live time days (1998-2003), 48 events with -1< $\cos(\theta)$ <-0.75 have been selected as clear neutrino events, compared to 56.6 events expected from an atmospheric neutrino MC (Bartol-96 flux [11] with oscillation parameters δm^2 =2.5$\cdot 10^{-3}$ eV^2 and full mixing, $\theta_m = \pi/4$; without oscillation 73.1 MC-events are expected); for details see [12, 13]. We find that absolute number and zenith angular distributions for MC and experimental data are within statistical uncertainties in good agreement.

Regarding the 48 detected events as being induced by atmospheric neutrinos, one can derive an upper limit on the additional flux of muons from the center of the Earth due to annihilation of neutralinos - the favored candidate for cold dark matter. From this, we obtain 90% C.L. muon flux limits for six cones around the opposite zenith (E_{thr} >10 GeV). From the strong

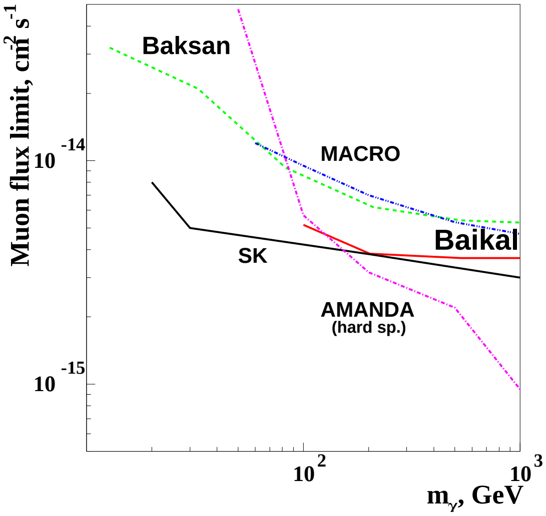

Figure 4: Limits on the excess of muon flux from the center of the Earth as a function of neutralino mass.

dependence of the size of the cone on the neutralino mass, see [14, 15, 16], we calculate 90% C.L. flux limits as function of neutralino mass. A correction is applied for each neutralino mass to translate from the experimental 10 GeV to 1 GeV threshold. These limits are shown in Fig.4. Also shown are limits obtained by Baksan [14], MACRO [15], Super-Kamiokande [16] and AMANDA (from the hard neutralino annihilation channels)[17].

2.3 A search for fast magnetic monopoles

Fast magnetic monopoles with Dirac charge $g = 68.5e$ are interesting objects to search for with deep underwater neutrino telescopes. The intensity of monopole Cherenkov radiation (for β=1) is $\approx$ 8300 times higher than that of muons. Optical modules of the Baikal experiment can detect such an object from a distance up to hundred meters. The processing chain for fast monopoles starts with the selection of events with a high multiplicity of hit channels: $N_{\rm hit} > 30$. Because of the high background of downward atmospheric muons, we restrict the search to upward moving monopoles. For an upward going particle, the times of hit channels increase with rising z-coordinates from bottom to top of the detector. To suppress downward moving particles, a cut on the value of the time–z–correlation, C_{tz}, is applied.

Within 1003 days of live time used in this analysis, about $3.3 \cdot 10^8$ events with $N_{\rm hit} \geq 4$ have been recorded, with 20943 of them satisfying cut 0 ($N_{\rm hit} > 30$ and $C_{tz} > 0$). For further background suppression (see [18] for details of the analysis) we use additional cuts, which essentially reject muon events and at the same time only slightly reduce the effective area for relativistic monopoles.

The upper limit on a flux of magnetic monopoles with $\beta = 1$ is $4.6{\cdot}10^{-17}$ cm^{-2}s^{-1}sr^{-1}. In Fig. 5 we compare our upper limit for an isotropic flux of fast monopoles obtained with the Baikal neutrino telescope [18] to the limits from the underground experiments Ohya [19] and MACRO [20], and from the underice detectors AMANDA-B10 [21] and AMANDA-II [22](preliminary).

We mention, that with an early NT200 prototype, a search for slow monopoles has been published [1] (β=10^{-5}–10^{-3} and for monopole catalyzed proton decay). An NT200-analysis, with improved sensitivity down to 10^{-17}cm^{-2}·s^{-1}·sr^{-1}, is in preparation.

2.4 A search for extraterrestrial high-energy neutrinos

The BAIKAL survey for high energy neutrinos searches for bright cascades produced at the neutrino interaction vertex in a large volume around the neutrino telescope [3]. We select events

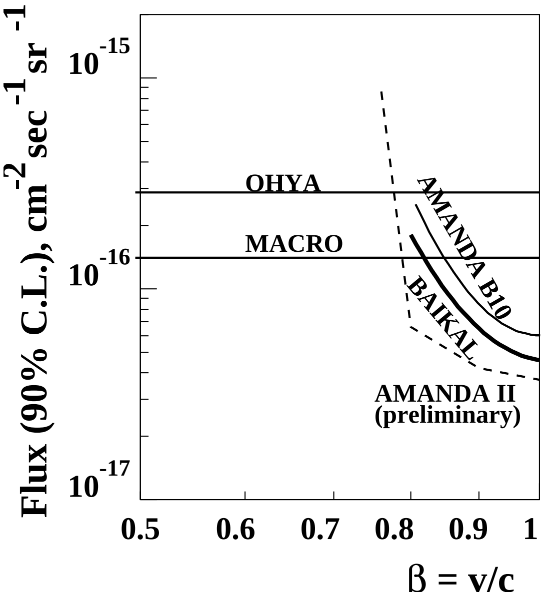

Figure 5: Upper limits on the flux of fast monopoles obtained in Baikal experiment [18] and in other experiments.

with high multiplicity of hit channels $N_{\rm hit}$, corresponding to bright cascades. To separate high-energy neutrino events from background events, a cut to select events with upward moving light signals has been developed. We define for each event $t_{\rm min} = \min(t_i - t_j)$, where t_i, t_j are the arrival times at channels i, j on each string, and the minimum over all strings is calculated. Positive and negative values of $t_{\rm min}$ correspond to upward and downward propagation of light, respectively.

The energy spectrum of neutrinos from galactic and cosmological sources or from the decay of topological defects is expected to have a significantly flatter shape than the spectrum of atmospheric muons and neutrinos. This gives rise to different N_{hit} and cascades energy distributions. Results of a search for high-energy neutrinos, based on N_{hit} as a rough indicator of the energy deposited in the effective detection volume were published in [3]. Here we present results of an exteneded analysis which is based on a full reconstruction of cascades parameters.

Within the 1038 days of the detector live time, 3.45×10^8 events with $N_{\rm hit} \geq 4$ have been recorded. For this analysis we used 22597 events with hit channel multiplicity $N_{\rm hit}$ >15 and $t_{\rm min}$ >-10 ns. As it was shown in [3] the data are consistent with simulated background for both $t_{\rm min}$ and $N_{\rm hit}$ distributions. A full cascade reconstruction algorithm (for vertex, direction, energy) was applied to the selected data. The experimental energy distribution is shown in Fig.6 (left panel: dots). Eight events were reconstructed as upward going cascades (distribution in dashed box in Fig.6). Also the MC-generated (histogram) and reconstructed (boxes) energy distributions from simulated atmospheric muons are shown in Fig.6 (left panel); 12 upward reconstructed cascade-like events are expected. From Fig.6 we conclude, that within the systematic and statistical uncertainties no significant excess above the background from atmospheric muons has been observed. To maximize the sensitivity to a neutrino signal we introduce the following cuts on allowed cascades energy: E_{sh} >130 TeV and E_{sh} >10 TeV for downward and upward going cascades, respectively.

With zero observed events and 2.3±1.2 expected background events for a 90% confidence level an upper limit on the number of signal events of $n_{90\%}$ =2.4 is obtained according to Conrad et al. [23] with the modified Feldman-Cousins ordering [24, 25].

A model of astrophysical neutrino sources, for which the total number of expected events, N_m, is larger than $n_{90\%}$, is ruled out at 90% CL. Table 1 represents event rates and model

Table 1: Expected number of events N_m and experimental model rejection factors for astrophysical neutrino source models.

	BAIKAL [3]		AMANDA [26, 27]
Model	$\nu_e + \nu_\mu + \nu_\tau$	$n_{90\%}/N_{\rm m}$	$n_{90\%}/N_{\rm m}$
SS05 Quasar [28]	0.71	3.4	1.6
P $p\gamma$ [29]	4.44	0.54	0.3
M $pp + p\gamma$ [30]	1.67	1.44	1.19
MPR [31]	1.37	1.75	0.9
SeSi [32]	2.40	1.00	-

rejection factors (MRF) $n_{90\%}/N_m$ for models of astrophysical neutrino sources obtained from our search, as well as model rejection factors obtained recently by the AMANDA collaboration [26, 27].

For an E^{-2} behaviour of the neutrino spectrum and a flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, the 90% C.L. upper limit on the neutrino flux of all flavors obtained with the Baikal neutrino telescope NT200 is:

$$E^2\Phi < 2.9 \times 10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}, \tag{1}$$

for $20\,\mathrm{TeV} < \mathrm{E}_\nu < 20\,\mathrm{PeV}$. For the resonant process at the resonance neutrino energy $E_0 = 6.3 \times 10^6$ GeV the model-independent limit on $\bar{\nu_e}$ is [3]:

$$\Phi_{\bar{\nu_e}} < 3.3 \times 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}. \tag{2}$$

Fig.6 (right panel) shows our upper limit on the all flavor E^{-2} diffuse flux (1) as well as the model independent limit on the resonant $\bar{\nu_e}$ flux (diamond) (2). Also shown are the limits obtained by AMANDA [26, 27] and MACRO [33], theoretical bounds obtained by Berezinsky for an E^{-2} shape of the neutrino spectrum (B) [34], by Waxman and Bahcall (WB) [35], by Mannheim et al.(MPR) [31], predictions for neutrino fluxes from topological defects (TD) [32], as well as the atmospheric conventional neutrino fluxes [36] from horizontal and vertical directions ((ν) upper and lower curves, respectively) and atmospheric prompt neutrino fluxes (ν_{pr}) from Volkova et al.[37].

3 Towards a km3 detector in Lake Baikal: the new technology string

The Baikal collaboration follows since several years an R&D program for an km3-scale neutrino telescope in Lake Baikal. The construction of NT200+ was a first step in this direction. The existing NT200+ is a natural laboratory to verify many new key elements and design principles of the new telescope.

A Baikal km3-detector could be made of building blocks similar to NT200+, but with NT200 replaced by a single string, still allowing separation of high-energy neutrino induced cascades from background [5]. It will contain a total of 1700–2300 optical modules (OMs), arranged at 90–100 strings with 16–24 OMs each, and an instrumented length of 350–460m. Interstring distances will be $\sim$100 m. The effective volume for cascades events above 100 TeV is 0.5–0.8 km^3, the threshold for muons is 10–30 TeV.

The most recent km3-milestone was the construction and installation of a "new technology" prototype string in spring 2008. This string is operating as an integral part of NT200+. Prototype string design and first results are described in detail in [38]. It is based on several new technology elements: (1) large area hemispherical PMTs (12" Photonis and 13" Hamamatsu, first time used in an underwater telescope), (2) 200MHz FADC readout technology, combined with string-based triggering and time synchronization by array trigger time-stamps, and (3) new

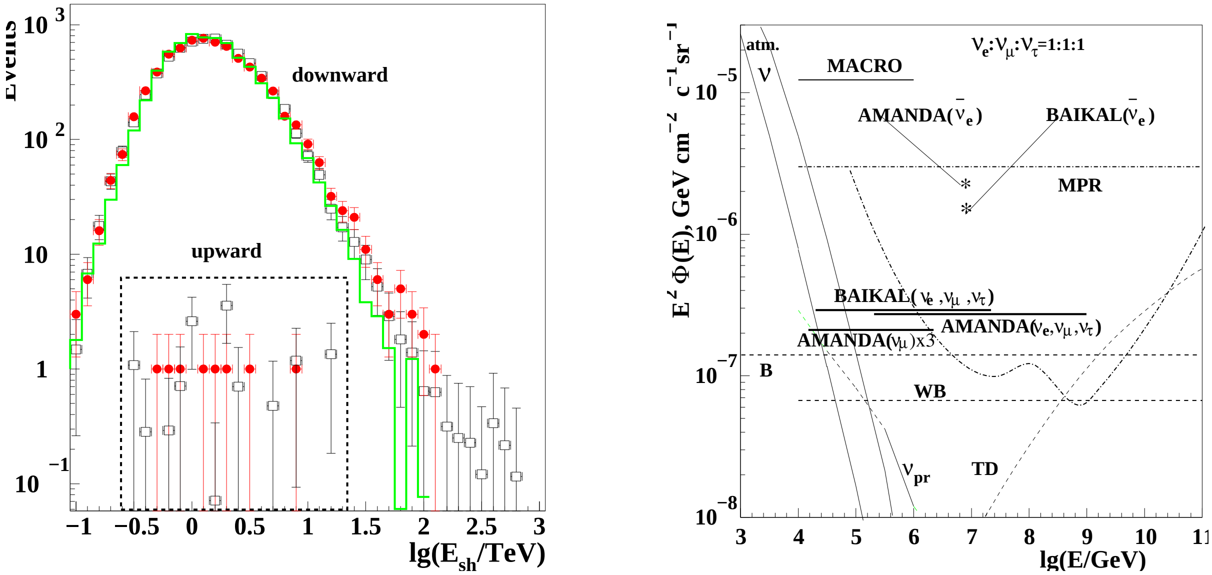

Figure 6: Left panel: Reconstructed cascade energy distribution for data (red dots) and for MC-generated atmospheric muons (boxes); true MC energy distribution given as histogram. Right panel: All-flavor neutrino flux bounds and predictions in different models of neutrino sources compared to experimental upper limits to E^{-2} fluxes obtained by this analysis and other experiments (see text).

calibration elements. Data collection & transmission is based on copper cables using proven DSL-technology (as in NT200+ [5]).

First calibration and verification tests have been successful. The string is now running in either of two operation modes: standalone atmospheric muon trigger, or in coincidence mode with NT200+ (high energy cascades). A detailed verification of the prototype string will be based on this large statistics data sample.

MC-optimization for the km3-detector design is going on, as well as studies for optimal trigger technologies. A technical design report for the new telescope is due for fall 2008.

4 Conclusion

The Baikal neutrino telescope NT200 is taking data since April 1998. With an improved method, based on casacde reconstruction and explicit energy cuts, the new upper limit obtained for a diffuse astrophysical $(\nu_e + \nu_\mu + \nu_\tau)$ E^{-2}-flux is $E^2\Phi = 2.9 \times 10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}$. The limits on the flux of fast magnetic monopoles and on a muon flux induced by WIMP annihilation at the center of the Earth belong to the most stringent limits existing to date. The limit on a $\bar{\nu}_e$ flux at the resonant energy 6.3×10^6GeV is presently the most stringent. NT200 also has a high sensitivity for exotic UHE atmospheric muon fluxes.

The significantly upgraded telescope NT200+, a detector with about 5 Mton enclosed volume, is operating since April 2005, and has an improved sensitivity for a diffuse flux of extraterrestrial neutrinos [5]. An ongoing feasibility study for acoustic UHE neutrino detection with a stationary antenna suggests that favourable conditions exist at Lake Baikal [7].

For the planned km3-scale neutrino detector in Lake Baikal, R&D-activities are in progress. An important km3-milestone was in Spring 2008 the installation of a new technolgy km3-prototype string, with full FADC-readout and large area hemisperical PMTs (12"/13"), which now operates together with NT200+. The km3-detector Technical Design Report is planned for fall 2008.

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