Status of the BAIKAL neutrino 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. Preparation towards a km3-scale (Gigaton volume) detector in Lake Baikal is currently a central activity. As an important milestone, a km3-prototype string, based on a completely new technology, has been installed and was put in operation together with NT200+ in April, 2008. We also present new results from the long-term operation of NT200, including an improved limit on the diffusive astrophysical neutrino flux.**

***Keywords*: neutrino telescopes, Baikal**

I. Introduction

The Baikal Neutrino Telescope NT200 is operating in Lake Baikal at a depth of 1.1 km and 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]. The most recent milestone of the ongoing km^3-telescope research and development work (R&D) was the installation of a new technology prototype string in spring 2008, as a part of NT200$+$ [6]. Fig.1 gives a sketch of the current status of the telescope NT200+, including the km^3-prototype string.

In this paper we discuss the R&D activities towards a km^3-scale Baikal telescope and review selected astroparticle physics results from long-term operation of NT200, in particular an improved limit on a diffusive astrophysical neutrino flux, and upper limits on muon flux from annihilation of hypothetical weakly interacting massive particles (WIMPs) in the Earth and the Sun. Limits on GRB-neutrino fluxes and new UHE-neutrino detection techniques are discussed in [7], [8].

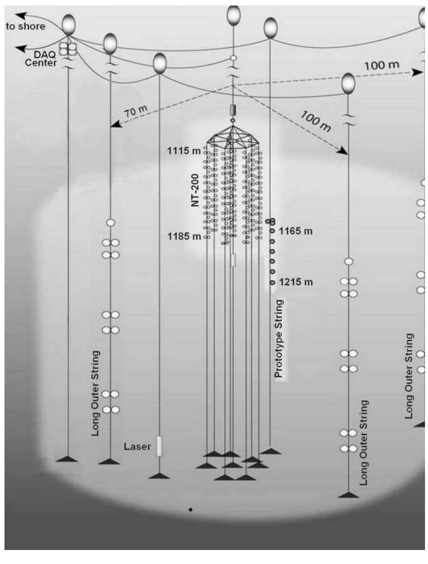

Fig. 1: The Lake Baikal neutrino telescope: the compact NT200 (center), 3 long outer strings and the new technology km^3-prototype string deployed in 2008.

II. Towards a km^3 detector in Lake Baikal: the new technology string

The Baikal collaboration follows since several years a R&D program for a km^3-scale neutrino telescope in Lake Baikal. The Baikal km^3-detector will have a relatively flexible structure, which allows for a rearrange-

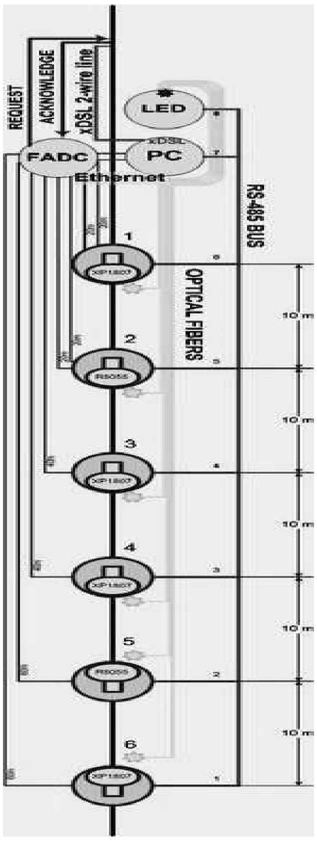

Fig. 2: The km^3-prototype string.

ment of the main building blocks (clusters), to adapt for requirements of new scientific goals, if necessary. The total number of 2100–2500 optical modules (OMs) will be arranged at 95–100 strings with 22–24 OMs each, and an instrumented length of 350–460 m. Interstring distances will be 80–120 m. The strings are grouped in 12–14 clusters which will form independent arrays. A total volume of 0.4–0.6 km^3 will be instrumented with photo-sensors. The effective area for muons above 20 TeV with an angular resolution of $0.5°$–$1°$ is 0.1–1 km^2, and the effective volume for cascade events above 100 TeV with angular resolution $2°$–$4°$ is 0.3–0.8 km^3.

The construction of NT200+ was a first step towards a km^3-scale neutrino telescope. NT200+ is a natural laboratory to verify many key elements and design principles of the new telescope. The most recent km^3-milestone was the construction and installation of a new technology prototype string in spring 2008. The basic goals of the 2008 prototype string installation are: investigation and in-situ test of basic elements of the future detector (new optical modules, DAQ system and cabling system); studies of the basic DAQ/triggering approach for the km^3-detector; comparison of the classical TDC/ADC approach with a FADC-based full pulse shape readout.

A. Prototype string design

The design of the prototype string is presented in Fig.2. The string consists of 6 new generation optical modules with photomultipliers R8055 (Hamamatsu) and XP1807 (Photonis). The distance between OMs along the string is 10 m. The upper 4 OMs have photomultipliers with downward looking photocathode, while the two bottom OMs contain PMs with upward looking photocathode. The preamplified dynode outputs of all 6 PMs are connected through underwater coaxial cables to 200 MHz FADC boards, located in a separate glass sphere. Two FADC channels are used to capture the waveforms of 2 additional low-gain channels of the two upper PMs.

Data from the FADC unit are transmitted via a local Ethernet line to the underwater micro-PC unit. Synchronization of prototype string and telescope data acquisition systems is the same as for the outer strings of NT200+ [3]. Time and amplitude calibration is provided by a string LED flasher located in a separate glass sphere near the FADC and PC units. Light pulses from the flasher are transmitted to each OM via optical fibers with calibrated length. Control and monitoring of OM and LED flasher operation is provided by the string PC unit via a RS-485 underwater bus.

B. First experimental results

The prototype string has been taking data since April 2008. Two basic modes of string operation are available: joint operation with NT200+ and standalone operation. A coincidence of a prototype string trigger with an external string trigger is necessary in the first mode of operation. This mode is used for investigations of cascade and muon events detected jointly with NT200+ and the new string, while the standalone mode is used for in-depth performance and stability verification with atmospheric muons and light calibration sources. In the second mode, a 3-fold coincidence of OMs of the prototype string is used as a trigger. Below, we present some preliminary results of tests of the string response to LED flasher and laser calibration sources in the standalone mode.

The first step of data analysis was a study of the accuracy of the pulse time measurement with the 200 MHz FADC. For this purpose, delayed pulses produced by the LED flasher were applied. An example of such a LED flasher event for the 3rd FADC channel is given in Fig.3. The first pulse is produced by LED1, the second by LED2. A pulse delay of 497 ns was installed by the LED flasher controller. For these two pulses, detection times and the corresponding delay were calculated from the FADC data. Two different approaches were used for the time calculation: a fit of the pulse leading edge and a full pulse shape fit, respectively. We find the average delay values to be close to the nominal value of 497 ns. Average RMS for the two methods are 2.8 ns and 1.8 ns, respectively.

A basic function of the LED flasher is the direct measurement of the relative time shifts of the spectrometric channels. Time shifts were determined as the time difference between pulses on different FADC channels for

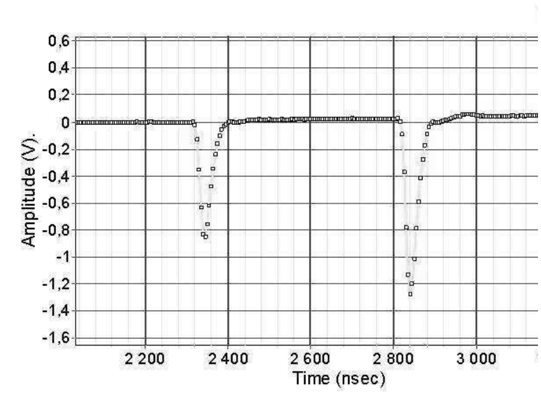

Fig. 3: Example of a two-pulse LED flasher event

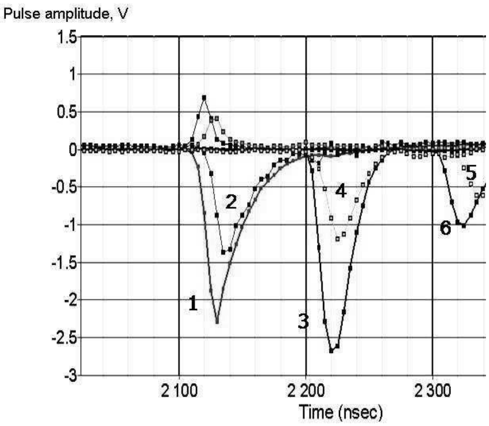

Fig. 4: Example of a LED flasher event detected with all FADC channels

simultaneously detected LED flashes. An example of a LED flasher event for this mode of operation is presented in Fig.4. In Fig.4, the indices indicate the OMs; positive pulses correspond to the low gain channels of the 1st and 2nd OM. Significant time differences between the pulses are caused mainly by differences in signal cable lengths, which are equal to about 20 meters for successive OM pairs. The time shifts were calculated taking into account the relative light pulse delay in the fiber optic cables for all channels.

The LED flasher also allows a direct amplitude calibration of the OM spectrometric channels. Two pulses with a delay of about 500 ns are produced by the LED flashers during the calibration. The first LED provides a small light pulse (single electron mode of phototube operation). The pulse of the second LED has a value significantly larger than the PM noise amplitude. This pulse is used as a trigger for the phototube dark noise suppression. Single electron spectra (SES) were measured in-situ for all OM phototubes. An average value of a single electron distribution is used as amplitude calibration coefficient for the given FADC channel.

The results of the time shift and amplitude calibration were used for the analysis of the prototype string calibration with the NT200+ laser light source, which is located at a horizontal distance of about 100 m from the string, and at about 1280 m depth (Fig.1). An example laser event, after time and amplitude calibration, is presented in Fig.5 (numbers indicate OMs). From a preliminary analysis of the laser data we conclude that the pulse arrival times are in good agreement with the expected values ($\sim$30 ns time difference between neighbouring OMs). A more detailed analysis, allowing to compare parameters of PMs of different types, is in progress now.

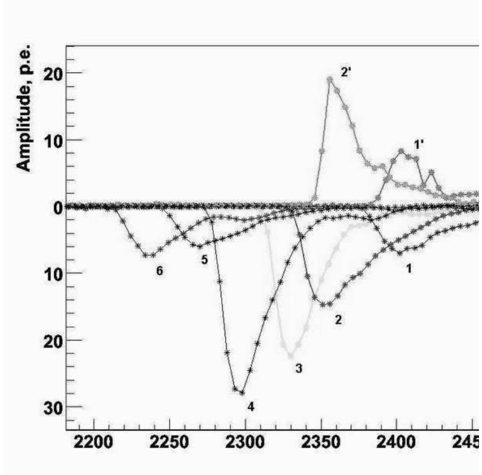

Fig. 5: Example of a laser event

An upgraded version of the prototype string, which comprises 12 optical modules, is operating in Lake Baikal since April 2009. MC-optimization for the km^3-detector design is going on, as well as studies for optimal trigger technologies.

III. Selected physics results from NT200

A. A Search for Neutrinos from WIMPs in the Earth and in the Sun

A possible signal from dark matter WIMP annihilations in the Earth and in the Sun would reveal as an excess of upward going muons over atmospheric neutrinos arriving either from near vertical or from the direction of the Sun, respectively. We have used the experimental data of NT200 taken between April, 1998 and March, 2003. In case of the Earth signal, event selection relies on a series of quality cuts which are tailored to the response of the telescope to nearly vertically upward going muons. The energy threshold is about $E_{thr} \sim 10$ GeV in this analysis. We have selected 48 neutrino events for 1038 live days, compared to 56.6 events expected from atmospheric neutrinos with the Super-Kamiokande oscillation parameters [9], and 73.1 events without oscillations. With no evidence for an excess above the atmospheric neutrino expectation, the upper limit at 90% confidence level (c.l.) on the muon flux from the center of the Earth was determined as $F < 3.7 \times 10^{-15}$ cm^{-2}s^{-1} (for WIMP masses greater than 100 GeV, and normalized to E_{thr} = 1 GeV).

In case of the Sun we have selected two data samples, adapted for the low and high WIMP mass region, with different BG admixture and angular reconstruction accuracy [10]. We have selected 510 and 2376 upward going muons in the two samples for 1008 live days, respectively. For both samples the distributions of correlation angles between these muons and the Sun were compared to the corresponding off-source background expectation. No indication for excess muons were found. The upper limit at 90% c.l. on an additional muon flux from the Sun is obtained as function of the WIMP mass for b anti-b (soft channel) and W^+W^- (hard channel) neutrino energy spectrum. For the WIMP masses greater than 500 GeV the limit depends weakly on the WIMP mass and is about $F < 3 \times 10^3$ km^{-2}yr^{-1} [10].

B. 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: $N_{\text{hit}} > 30$. To suppress a background from atmospheric muons, a cut on the value of the time–z–correlation, C_{tz}, is applied (see for details [11]). The data corresponding to 1003 days of live time were used in this analysis. No excess over the expected background were found. The 90% c.l. upper limit on the magnetic monopole flux with $\beta = 1$ is 4.6$\times$10^{-17} cm^{-2}s^{-1}sr^{-1}.

C. 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 telescope. A full cascade reconstruction algorithm (for vertex, direction, energy) was applied to the 1038 live days data taken with NT200 in 1998-2002 years [12], [8]. Within systematic and statistical uncertainties there is no significant excess above the background from atmospheric muons. Cuts were then placed on this reconstructed cascade energy to select neutrino events. With zero observed events and 2.3$\pm$1.2 expected background events, a 90% c.l. upper limit on the number of signal events of $n_{90\%}$ =2.4 is obtained. Upper limits on diffuse neutrino fluxes predicted by several theoretical models of AGN-like astrophysical sources were derived [12]. 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

$$E^2\Phi < 2.9 \times 10^{-7}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}, \qquad (1)$$

for $20\,\text{TeV} < \text{E}_\nu < 20\,\text{PeV}$.

IV. Conclusion

The Baikal neutrino telescope NT200 is working since April 1998. The upper limit obtained for a diffuse astrophysical $(\nu_e + \nu_\mu + \nu_\tau)$ E^{-2}-flux is $E^2\Phi = 2.9 \times 10^{-7}$cm^{-2}s^{-1}sr^{-1}GeV. The limits on the flux of fast magnetic monopoles and on the muon fluxes induced by WIMP annihilation at the center of the Earth and the Sun belong to the most stringent limits existing to date.

On the road towards a km^3-scale neutrino telescope in Lake Baikal, significant upgrades of the detector have been done in spring 2005. The upgraded telescope NT200+, a detector with about 5 Mton enclosed volume, has an improved sensitivity for a diffuse flux of extraterrestrial neutrinos. For the planned km^3-scale neutrino detector in Lake Baikal, R&D-activities are in progress. NT200+ is a natural laboratory to verify many key elements and design principles of the new telescope. An important km^3-milestone was the Spring 2008 installation of a new technology km^3-prototype string, with full FADC-readout and large area hemispherical PMs (12"/13"), which was operating together with NT200+. An upgraded version of the prototype string, which comprises 12 optical modules, is operating in Lake Baikal since April 2009. The km^3-detector Technical Design Report is planned for fall 2010.

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