The Baikal Experiment - from Megaton to Gigaton

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\textbf{Abstract}. We review the status of the Lake Baikal Neutrino Experiment. Preparation towards a km\textsuperscript{3}-scale Gigaton Volume Detector (GVD) in Lake Baikal is currently a central activity. As an important milestone, a km\textsuperscript{3}-prototype string comprising 6 optical modules and based on a completely new technology, has been installed and was put into operation together with NT200\textsuperscript{+} in April, 2008. An upgraded version of the prototype string, which comprises 12 optical modules, was put into operation in April 2009. We also present new results from the long-term operation of NT200, including an improved limit on the diffuse astrophysical neutrino flux.

The Baikal Neutrino Telescope NT200 is taking data since 1998 in Lake Baikal. Since 2005, the upgraded 10-Mton scale detector NT200\textsuperscript{+} is in operation. Detector configuration and performance have been described elsewhere [1, 2, 3, 4, 5]. The most recent milestone of the ongoing km\textsuperscript{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\textsuperscript{+} [6]. Fig.1 gives a sketch of the current status of the telescope NT200\textsuperscript{+}, including the km\textsuperscript{3}-prototype string.

In this paper we discuss the R\&D activities towards a km\textsuperscript{3}-scale Baikal telescope and review recent astroparticle physics results from long-term operation of NT200 - an improved limit on a diffuse astrophysical neutrino flux, and upper limit on muon flux from annihilation of WIMPs in the Sun.
1. 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 rearrangement 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 60–80 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 10 TeV with an angular resolution of $0.5^\circ–1^\circ$ is 0.1–1 km$^2$, and the effective volume for cascade events above 100 TeV with angular resolution $\sim 5^\circ$ is 0.3–0.8 km$^3$. MC-optimization for the km$^3$-detector design is going on, as well as studies for optimal trigger technologies.

The basic goals of the prototype string installation are: investigation and in-situ test of basic elements of the future detector (new optical modules, DAQ system and cable 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. The design of the prototype string is presented in Fig.2. The string consists of 6 optical modules with photomultipliers R8055 (Hamamatsu) and XP1807 (Photonis). The distance between OMs along the string is 10 m. 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. 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 are provided by the string PC unit via a RS-485 underwater bus. Two basic modes of string operation are available: joint operation with NT200+ and standalone operation.
Below, we present some preliminary results of tests of the string response to LED flasher and laser calibration sources in the standalone mode.

The accuracy of the pulse time measurement with the 200 MHz FADC was studied by using two pulses of LED flasher, which were delayed on 497 ns. We find the average delay values, calculated from the FADC data, to be close to the nominal value of 497 ns with average RMS of 1.8 ns. A basic function of the LED flasher is the direct measurement of the relative time shifts and a direct amplitude calibration of the spectrometric channels. Time shifts were determined as the time difference between pulses on different FADC channels for simultaneously detected LED flashes. Two pulses with a delay of about 500 ns are produced by the LED flashers during the amplitude calibration. The first LED provides a light pulse at single electron level. The second LED has a value significantly larger than the PM noise amplitude and is used as a trigger for the phototube dark noise suppression. 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. From a preliminary analysis of the laser data we conclude that the pulse arrival times are in good agreement with the expected values.

2. Recent physics results from NT200
A possible signal from dark matter WIMP annihilations in the Sun would reveal as an excess of upward going muons over atmospheric neutrinos arriving from the direction of the Sun. We have used the experimental data of NT200 taken between April, 1998 and March, 2003 (1008 live days). No indication for excess muons was 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 $F < 3 \times 10^4 \text{km}^{-2}\text{yr}^{-1}$ [7].

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 [8]. Cuts were then placed on this reconstructed cascade energy to select neutrino events. No neutrino events were found. Upper limits on diffuse neutrino fluxes predicted by several theoretical models of AGN-like astrophysical sources were derived [8]. For an $E^{-2}$ neutrino spectrum the 90% c.l. upper limit on the neutrino flux of all flavors obtained with the Baikal neutrino telescope NT200 is: $E^2\Phi < 2.9 \times 10^{-7}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}$.

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