The BAIKAL experiment: status, selected results, and prospects


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Abstract. We review the status of the Baikal Neutrino Telescope, which has recently been upgraded to the 10 Mton detector NT200+. We present results on searches for upward going atmospheric neutrinos and relativistic magnetic monopoles, obtained from 1998-2002 with the predecessor detector NT200. A search for very high energy neutrinos yields an upper limit on the extraterrestrial diffuse neutrino flux for $20\text{ TeV} < E < 50\text{ PeV}$. We describe the strategy of creating a detector on the Gigaton (km$^3$) scale at Lake Baikal. R&D activities on that next stage detector have been started.

1. Introduction

The Baikal Neutrino Telescope is operated in Lake Baikal, Siberia, at a depth of 1.1 km. The first stage telescope configuration NT200 was put into permanent operation on April 6th, 1998 and consists of 192 optical modules (OMs). Detector design and site properties are described elsewhere [1, 2, 3].

On April 9th, 2005, the 10-Mton scale detector NT200+ was put into operation [4]. A schematic view of NT200+ is shown in Fig.1. The detector comprises NT200, as well as three additional 140 m long external strings. Each external string is placed 100 m from the center of NT200 and holds 12 pairwise arranged OMs. On each external string, an independent string trigger is formed in case the number of fired channels is $\geq 2$ within 1000 ns. For time offset
calibration of the external strings with respect to NT200, a laser light source is used (see Figure 1, bottom left). The jitter of the time difference between OMs of NT200 and OMs of external strings was found to be less than 3 ns. With the additional strings, the sensitivity of the Baikal telescope to very high energy neutrinos increases by a factor 4.

We are presenting results obtained with NT200 data taken from 1998-2002: atmospheric muon neutrino detection and searches for relativistic magnetic monopoles and extraterrestrial high energy neutrinos. NT200+ will be used as the basic cell of a future Gigaton detector in Lake Baikal, which is briefly sketched.

2. Selected results obtained with 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 [2]. Compared to [2], the analysis of the 5-year sample (1038 days live time) was optimized for higher signal passing rate, and accepting a slightly higher contamination of 15-20% fake events. 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. The skyplot of these events is shown in Fig. 2.

2.2. 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 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: $N_{hit} > 30$. In order to reduce the background from downward atmospheric muons we restrict ourself to monopoles coming from the lower hemisphere. For an upward going particle the times of hit channels increase with rising $z$-coordinates from bottom to top of the detector. To suppress events caused by downward
moving particles, a cut on the value of the time–z–correlation, $C_{tz}$, is applied:

$$C_{tz} = \frac{\sum_{i=1}^{N_{hit}} (t_i - \overline{t})(z_i - \overline{z})}{N_{hit}\sigma_t\sigma_z} > 0$$

where $t_i$ and $z_i$ are time and z-coordinate of a fired channel, $\overline{t}$ and $\overline{z}$ are mean values for times and z-coordinates of the event and $\sigma_t$ and $\sigma_z$ the rms errors for time and z-coordinates. In Fig. 3 we compare the $C_{tz}$-distribution for experimental data (triangles) with expected distribution for atmospheric muons (solid curve), as well as for upward moving relativistic monopoles (dotted curve). Within 1003 days of live time used in this analysis, about $3 \times 10^8$ events with $N_{hit} > 4$ have been recorded, with 27003 of them satisfying cut 0 ($N_{hit} > 30$ and $C_{tz} > 0$). For further background suppression (see [5] 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.

No events from the experimental sample pass all cuts. For the time periods included in the analysis the acceptances $A_{eff}$ varies between $3 \times 10^8$ and $6 \times 10^8\text{cm}^2\text{sr}$ (for $\beta = 1$). From the non-observation of candidate events in NT200 and the earlier stage telescopes NT36 and NT96 [6], a combined 90% C.L. upper limit on the flux of fast monopoles is obtained. In Fig. 4 we compare this upper limit to the limits from the underground experiments Ohya [7] and MACRO [8] and to the limit reported for the underice detector AMANDA [9]. The Baikal limit is currently the most stringent one.

2.3. 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 [10]. We select events with high multiplicity of hit channels $N_{hit}$, 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 $t_{min} = \min(t_i - t_j)$, 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 $t_{\text{min}}$ correspond to upward and downward propagation of light, respectively.

Within the 1038 days of the detector live time between April 1998 and February 2003, $3.45 \times 10^8$ events with $N_{\text{hit}} \geq 4$ have been recorded. For this analysis we used 22597 events with hit channel multiplicity $N_{\text{hit}} > 15$ and $t_{\text{min}} > -10$ ns. We conclude that data are consistent with simulated background for both $t_{\text{min}}$ and $N_{\text{hit}}$ distributions. No statistically significant excess above the background from atmospheric muons has been observed. Since no events have been observed which pass the final cuts, upper limits on the diffuse flux of extraterrestrial neutrinos are calculated. For a 90% confidence level an upper limit on the number of signal events of $n_{90\%} = 2.5$ is obtained assuming an uncertainty in signal detection of 24% and a background of zero events. A model of astrophysical neutrino sources, for which the total number of expected events ($\nu_e + \nu_\mu + \nu_\tau$), $N_{\text{model}}$, is larger than $n_{90\%}$, is ruled out at 90% CL. Table 1 represents event rates and model survival factors (MSF) $n_{90\%}/N_{\text{model}}$ for models of astrophysical neutrino sources obtained from our search, compared to AMANDA [11, 12, 13].

For an $E^{-2}$ behaviour of the neutrino spectrum and a flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at the Earth, the 90% C.L. upper limit on the neutrino flux of all flavors obtained with the Baikal neutrino telescope NT200 (1038 days) is [10]:

$$E^2 \Phi < 8.1 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}.$$  \hspace{1cm} (2)

For the resonant process with the resonant neutrino energy $E_0 = 6.3 \times 10^6 \text{GeV}$, the model-independent limit on $\bar{\nu}_e$ is [10]:

$$\Phi_{\bar{\nu}_e} < 3.3 \times 10^{-20} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}.$$  \hspace{1cm} (3)

Fig. 5 shows our upper limit on the all-flavor $E^{-2}$ diffuse flux (2) as well as the model independent limit on the resonant $\bar{\nu}_e$ flux (diamond) (3). Also shown are the limits obtained by AMANDA [11, 12, 13] and MACRO [21], theoretical bounds obtained by Berezinsky (model independent (B)) [22] and for an $E^{-2}$ shape of the neutrino spectrum (B($E^{-2}$)) [23], by Waxman and Bahcall (WB) [24], by Mannheim et al. (MPR) [19], predictions for neutrino fluxes from topological defects (TD) [20], prediction on diffuse flux from AGNs according to Nellen et al. (NMB) [25], as well as the atmospheric conventional neutrino fluxes [26] from horizontal and vertical directions ($\nu$ upper and lower curves, respectively) and atmospheric prompt neutrino fluxes ($\nu_{\mu\tau}$) obtained by Volkova et al. [27].

**Table 1.** Expected number of events $N_{\text{model}}$ and model survival factors for models of astrophysical neutrino sources.

<table>
<thead>
<tr>
<th>Model</th>
<th>$N_{\text{model}}$ ($\nu_e + \nu_\mu + \nu_\tau$)</th>
<th>$n_{90%}/N_{\text{model}}$</th>
<th>AMANDA [11, 12, 13] $n_{90%}/N_{\text{model}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-6} \times E^{-2}$</td>
<td>3.08</td>
<td>0.81</td>
<td>0.86</td>
</tr>
<tr>
<td>SS Quasar [14]</td>
<td>10.00</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>SS Quasar [15]</td>
<td>1.00</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>SP u [16]</td>
<td>40.18</td>
<td>0.062</td>
<td>0.054</td>
</tr>
<tr>
<td>SP l [16]</td>
<td>6.75</td>
<td>0.37</td>
<td>0.28</td>
</tr>
<tr>
<td>P $\gamma$ [17]</td>
<td>2.19</td>
<td>1.14</td>
<td>1.99</td>
</tr>
<tr>
<td>M $pp + \gamma$ [18]</td>
<td>0.86</td>
<td>2.86</td>
<td>1.19</td>
</tr>
<tr>
<td>MPR [19]</td>
<td>0.63</td>
<td>4.0</td>
<td>4.41</td>
</tr>
<tr>
<td>SeSi [20]</td>
<td>1.18</td>
<td>2.12</td>
<td>-</td>
</tr>
</tbody>
</table>
3. A Gigaton Volume Detector at Baikal

MC simulations have shown that the detection volume of NT200+ for PeV cascades would vary only moderately, if NT200 as the central part of NT200+ is replaced by a single string of OMs. For neutrino energies higher than 100 TeV, such a configuration could be used as a basic unit of a Gigaton Volume Detector (GVD). Rough estimations show that 0.7 ÷ 0.9 Gton detection volume (i.e. 0.7 - 0.9 km$^3$) for neutrino induced high energy cascades may be achieved with about 1300 - 1500 OMs arranged at 90 - 100 strings. A top view of a GVD toy configuration as well as a sketch of one basic subarray are shown in Fig. 6. Figure 7 shows the detection volume as function of energy for cascades induced by neutrinos within the geometric volume. The high water transparency and the low light scattering in Lake Baikal allow for a precise reconstruction of cascade vertex and energy. Figure 8 illustrates the efficiency of the cascade energy reconstruction procedure. The physics capabilities of GVD at very high energies cover the typical spectrum of cubic kilometer arrays.

4. Conclusion

The Baikal neutrino telescope NT200 is taking data since April 1998. The upper limit obtained for a diffuse ($\nu_e + \nu_\mu + \nu_\tau$) flux with $E^{-2}$ shape is $E^2 \Phi = 8.1 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV. The limits on fast magnetic monopoles and on a diffuse $\bar{\nu}_e$ flux at the resonant energy 6.3 x 10$^6$ GeV are presently the most stringent ones. To extend the search for diffuse extraterrestrial neutrinos with higher sensitivity, NT200 was significantly upgraded to NT200+, a detector with about 5 Mton enclosed volume, which takes data since April 2005. The three-year sensitivity of NT200+ to the all-flavor neutrino flux is approximately $2 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV for $E > 10^2$ TeV (shown in Fig. 5). NT200+ will search for neutrinos from AGNs, GRBs, galactic and other extraterrestrial sources, as well as high energy atmospheric muons with $E_\mu > 10$ TeV.

For the planned km$^3$-detector in Lake Baikal, R&D-activities have recently been started. With
Shower energy, lg(E/TeV)

Detection volume, m$^3$

Figure 7. Detection volume of the GVD detector vs. cascade energy.

Reconstructed energy, lg(E/TeV)

Events

Figure 8. Energy reconstruction for cascades detected by the GVD detector.

a Technical Design Report scheduled for 2008, deployment will start in 2010.

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