Proceedings of ICRC 2001: 1096 © Copernicus Gesellschaft 2001

ICRC 2001

The Lake Baikal Neutrino Experiment

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Abstract. We review the present status of the Baikal Neutrino Project and present the results obtained with the deep underwater neutrino telescope *NT–200*

1 Introduction

The Baikal Neutrino Telescope is deployed in Lake Baikal, Siberia, 3.6 km from shore at the depth of 1.1 km. The present stage of the telescope, *NT–200*, (Belolaptikov et al., 1997), was put into operation at April, 1998. Telescope consists of 192 optical modules (OMs). An umbrella-like frame (see Fig.1) carries 8 strings, each with 24 pairwise arranged OMs. Three underwater electrical cables and one optical cable connect the detector with the shore station. Deployment of all detector components is carried out during seven week in late winter when the lake is covered by a thick layer of ice.

The OMs contain large area hybrid phototube *QUASAR – 370*, with a hemispherical photocathode of 37 cm diameter and a time resolution better than 3 ns (Bagduev et al., 1999). The OMs are grouped in pairs along the strings. The pulses from two PMs after 0.3 *p.e.* discrimination are fed to a coincidence with 15 ns time window in order to suppress background from bioluminescence and PM noise. A pair defines a *channel*.

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, 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. The calibration of the relative time shifts between all channels is performed using a laser, positioned above the array. The light from this laser is guided by optical fibers of equal length to each OM pair. To cross check this method, a special second laser, with the same characteristic, emitting light directly through the water was fixed at the central string 20 m below the bottom layer of OMs (not shown on Fig. 1).

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2 Experimental work during the last expedition

2.1 Study of acoustic signals from EAS

We continued to study the feasibility of acoustic detection of EAS cores (Balkanov et al., 2001). This winter the EAS array was deployed at a distance of 1.5 km from the main ice camp in order to decrease the electromagnetic and acoustic crosstalk on hydrophones. The EAS array consisted of seven scintillators (0.5 m^2). Six detectors were placed at the corners of a hexagon and one in the center. The distances between central and peripheral detectors were 80 m. Four hydrophones were placed 34 m apart from the center of the EAS array at a depth of 5 m [1]. During the EAS array life time of 154 hours, almost 2400 showers with energies above 5 PeV have been recorded. Coincidence data of the EAS array and hydrophones are presently analyzed.

2.2 Study of the water parameters

In the winter expedition of this year we continued our measurements of optical parameters of the water at the telescope

[1]One of hydrophones was installed by the ITEP team (Moscow) 20 m apart from the center of the EAS array.

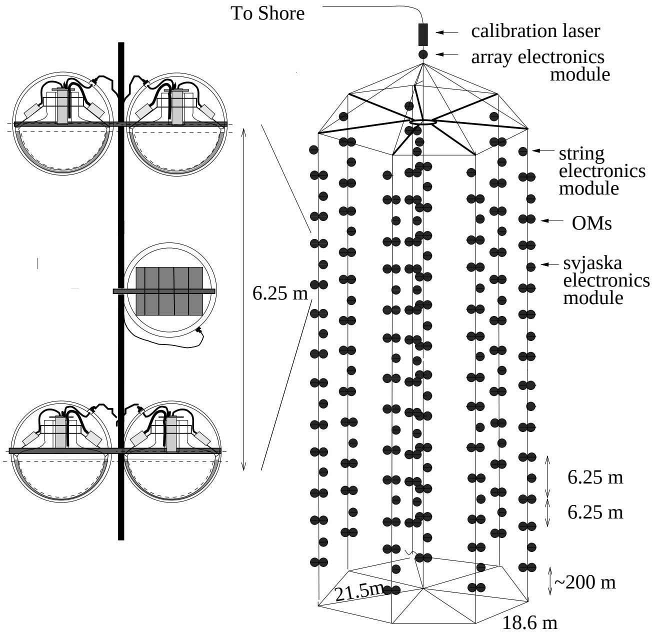

Fig. 1. Schematic view of the Baikal neutrino telescope.

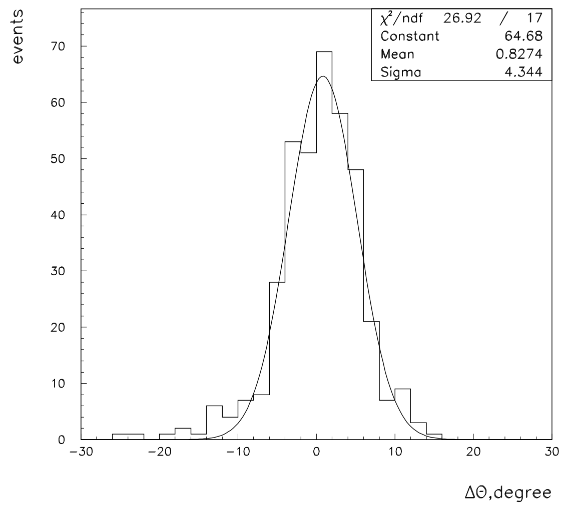

Fig. 2. Distribution of the difference of zenith angles, measured by the EAS array and *NT–200*. The gaussian fit has a mean of 0.82^o and σ of 4.3^o.

site. Since the good knowledge of these quantities is essential for underwater neutrino experiments, independent measurements of the NEMO group (A.Capone et al.) have been performed at the same time. The data of these measurements are under analysis now. Preliminary results indicate that the two independent sets of optical data are compatible.

2.3 Technology test string

A special string for diverse goals has been operated in the course of the last expedition at the lake. With instruments at this string we have measured the group velocity of light in water at two different wavelengths and tested a two-channel optical module and a calibration light beacon. The two latter items are discussed in more detail elsewhere in these proceedings.

3 Study of the telescope angular resolution

During three winter seasons, starting with 1998, a Cherenkov EAS array, consisting of four *QUASAR–370* phototubes was deployed on the ice, just above the underwater telescope, with the aim to study the angular resolution of the latter. The angular resolution of the EAS array is better than 1^o. The full statistics of coincidence events is nearly 600. The main part of these events have a zenith angle smaller than 15^o. Due to the relatively high energy threshold of the EAS array (200 TeV) nearly all these events are multi-muon events. For such events our standard track reconstruction procedure (Balkanov et al. 1999) doesn't work properly, but zenith angles of nearly vertical multi-muon events can be reconstructed under the assumption the OMs along a single string are mostly illuminated by only one of these muons. Fig.2 shows the distribution of the difference of the zenith angles reconstructed by the EAS array and by the underwater telescope, respectively. The number of hit channels was requested to be ≥ 5. The distribution can be fitted by a gaussian distribution with $\sigma = 4.3^o$. This value decreases slightly (to 3.8^o) if only events with ≥ 6 hit channels on the one string are used. From this analysis we can conclude that the angular resolution of underwater telescope for vertical muons is about 4^0.

4 Selected physics results

4.1 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. The algorithm uses a single muon model to reconstruct events. We first reject hits, which are likely due to dark current or water luminescence, as well as hits which are due to showers and have large time delays with respect to the expected hit times from single-muon Cherenkov light. The reconstruction yields a fraction of about $4.6 \cdot 10^{-2}$ of triggered events which are reconstructed as upward going, with the trigger $\geq 6/3$ (at least 6 hits on at list 3 strings). This 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 a set of quality cuts (Balkanov et al., 2001) If the event doesn't obey any of chosen criteria, it is rejected as wrongly reconstructed. Different to *NT-96* (Belolaptikov et al.,1999), the neutrino selection algorithm for *NT-200* starts with a offline trigger $\geq 7/3$. The efficiency of the procedure and correctness of the MC background estimation have

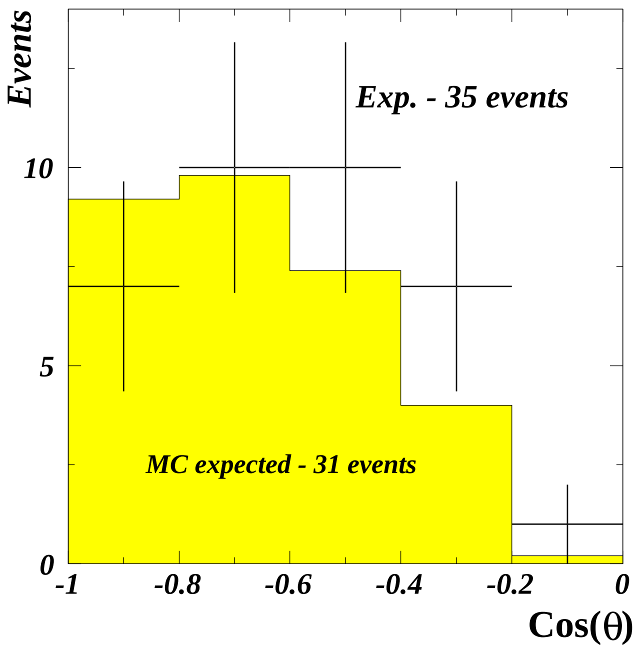

Fig. 3. Experimental angular distribution of reconstructed upward going muons in *NT–200*. Filled histogram – MC expectation

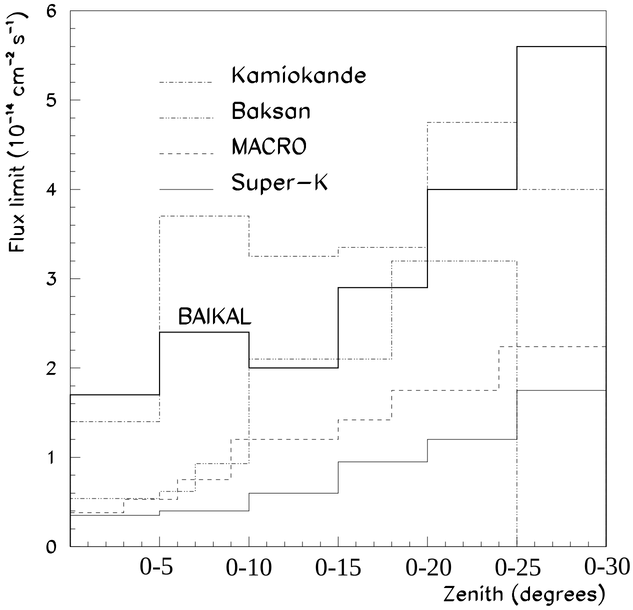

Fig. 4. Comparison of Baikal limits on nearly vertically upward muons with those from other experiments.

been tested with a sample of $2.8 \cdot 10^6$ MC-generated from atmospheric muons and with MC-generated upward going muons due to atmospheric neutrinos. None of MC background events has passed all cuts. Data taken with *NT-200* between 1998 April and 1999 February cover 234 days life time. For this period we got $5.3 \cdot 10^7$ events with trigger $\geq 6/3$. The set of 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.3.

4.2 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, compared to the expectation for atmospheric neutrinos.

Different to 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 (Balkanov et al., 2001; Bezrukov et al., 1995; Balkanov et al., 1999). 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, with at least one string containing ≥4 hits. To this sample , a series of 6 cuts is applied. 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 2500 m^2. After applying all cuts, ten events were selected as neutrino candidates, compared to 8.9 expected from atmospheric neutrinos. 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 comparison of Baikal flux limits with those obtained by Baksan (Boliev et al., 1996; Suvorova, 1999), MACRO (Montaruli et al,,1999), Kamiokande (Mori et al., 1993) and Super-Kamiokande (Okada,,2000) is shown in fig.4.

4.3 Search for relativistic magnetic monopoles ($\beta > 0.75$)

Relativistic 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) .

The natural way to search for fast monopoles is based on a 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 ourself to monopoles coming from the lower hemisphere.

To select events from monopoles, in the present analysis of the data from the first 234 live days of *NT-200*, we used cuts on the number of hit channels, on the value of the space-time correlation, on the time difference of hit channels and the value of amplitude in the two channels with maximum am-

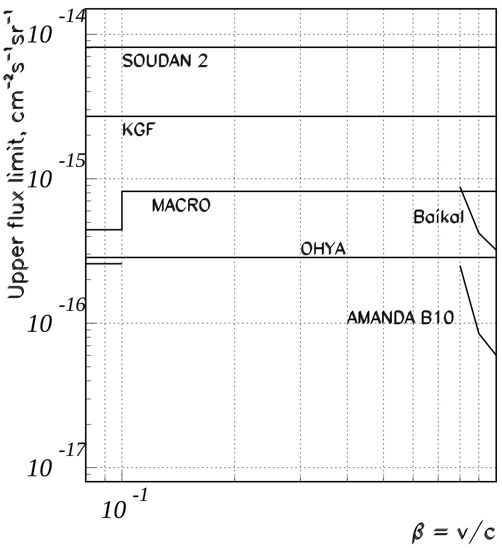

Fig. 5. Upper limits on the flux of fast monopoles obtained in different experiments.

plitudes (Balkanov et al.,2001). 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* and *NT-200* as well as limits from underground experiments MACRO, Soudan2, KGF, Ohya and AMANDA (Ambrosio et al., 1999; Thorn et al., 1992; Adarkar et al., 1990; Orito et al.; Niessen, 2000) are shown in Fig.5.

4.4 A search for very high energy neutrinos

An upper limit on $(\nu_e + \tilde{\nu_e})$ diffuse flux of $E^2\Phi_\nu(E) < (1.2\div 1.9)\cdot 10^{-6}$ cm^{-2} s^{-1} sr^{-1} GeV within neutrino energy range $10^4 \div 10^7$ GeV is obtained, assuming an E^{-2} behavior neutrino spectrum and flavor ratio $(\nu_e + \tilde{\nu_e}) : (\nu_\mu + \tilde{\nu_\mu})$= 1:2. For more details see our paper covering this issue elsewhere in this proceding.

5 Conclusion

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, the effective volume of *NT-200* for high energy electron and tau neutrinos detection is several megatons and exceeds the geometrical volume by a factor of about 50 at highest energies. This will permit a search for diffuse neutrino fluxes from AGN and other extraterrestrial sources down to the level of theoretical predictions. With an effective area two times larger than Super-Kamiokande, for nearly vertically upward muons (E_μ >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.

Acknowledgements. This work was supported by the Russian Ministry of Research (contract 102-11(00)-p), the German Ministry of Education and Research and the Russian Fund of Basic Research (grants 99-02-1837a,01-02-31013 and 00-15-96794) and by the Russian Federal Program "Integration"(project 346).

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