Nearly Vertical Muons From the Lower Hemisphere in the BAIKAL Neutrino Experiment

K. Antipin [a], V. Aynutdinov [a], V. Balkanov [a], I. Belolaptikov [d], N. Budnev [b], I. Danilchenko [a], G. Domogatsky [a], A. Doroshenko [a], A. Dyachok [b], Zh. Dzhilkibaev [a], S. Fialkovsky [f], O. Gaponenko [a], K. Golubkov [d], O. Gress [b], T. Gress [b], O. Grishin [b], A. Klabukov [a], A. Klimov [h], A. Kochanov [b], K. Konischev [d], A. Koshechkin [a], V. Kulepov [f], L. Kuzmichev [c], E. Middell [e], S. Mikheyev [a], T. Mikolajski [e], M. Milenin [f], R. Mirgazov [b], E. Osipova [c], G. Pan'kov [b], L. Pan'kov [b], A. Panfilov [a], D. Petukhov [a], E. Pliskovsky [d], P. Pokhil [a], V. Polecshuk [a], E. Popova [c], V. Prosin [c], M. Rosanov [g], V. Rubtzov [b], B. Shaibonov [d], A. Sheifler [a], A. Shirokov [c], Ch. Spiering [e], B. Tarashansky [b], R. Wischnewski [e], I. Yashin [c], V. Zhukov [a]

[a] *Institute for Nuclear Research, Moscow, Russia*
[b] *Irkutsk State University, Irkutsk, Russia*
[c] *Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia*
[d] *Joint Institute for Nuclear Research, Dubna, Russia*
[e] *DESY, Zeuthen, Germany*
[f] *Nizhni Novgorod State Technical University, Nizhni Novgorod, Russia*
[g] *St Petersburg State Marine University, St Petersburg, Russia*
[h] *Kurchatov Institute, Moscow, Russia*

Abstract

We present the results of a search for nearly vertically upward going neutrino-induced muons with 1038 live days data from the neutrino telescope NT200 taken over the five year period 1998-2002. No excess from WIMP annihilation in the Earth above the expected atmospheric neutrino background has been found. Upper limits at 90% confidence level have been derived on the moun flux induced by neutrinos from WIMP annihilation.

1. Introduction

The Baikal Neutrino Telescope is operated in Lake Baikal, Siberia, at a depth of 1.1 km. Lake Baikal deep water is characterized by an absorption length of L_{abs}(480 nm)=20÷24 m, a scattering length of L_s =30÷70 m and a strongly anisotropic scattering function $f(\theta)$ with a mean cosine of the scattering angle $\overline{\cos}(\theta) = 0.85 \div 0.9$. The first stage telescope configuration NT200 [1] was put into permanent operation on April 6th, 1998 and consists of 192 optical modules (OMs). An umbrella-like frame carries 8 strings, each with 24 pairwise arranged OMs (see central part of Fig. 1 left panel). All OMs face downward, with the exception of the second and eleventh pairs on each string which face upward. Three underwater electrical cables connect

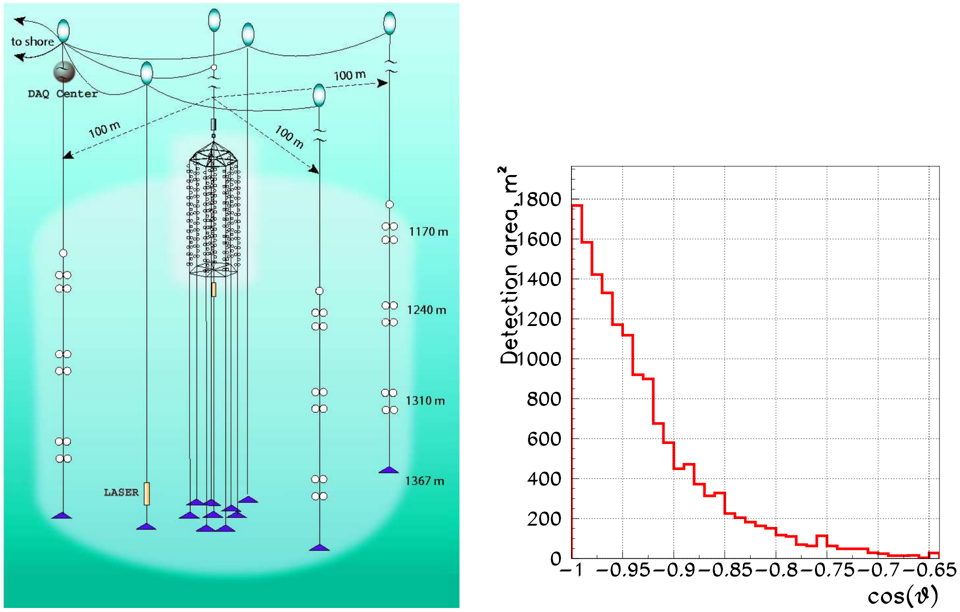

Fig. 1. Left: The upgraded Baikal Telescope NT200+ : The old NT200 surrounded by three external long strings at 100 m radius from the center. Also indicated: external laser and DAQ center. Right: Detection area after WIMP cuts as a function of zenith angle.

the detector with the shore station. Each OM contains a 37-cm diameter *QUASAR* - photo multiplier (PM), which has been developed specially for our project [2]. The PMs record the Cherenkov light produced by charged particles in water. The two PMs of a pair are switched in coincidence in order to suppress background from bioluminescence and PM noise. A pair of OMs defines a *channel*. The light arrival time assigned to a channel is the response time of the OM with the earliest hit. The amplitude assigned to a channel is that recorded by one pre-selected PM of the two PMs in a pair.

A *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 these events, amplitude and time of all fired channels are digitized and sent to shore.

Two nitrogen lasers are used for the calibration of the detector. The first one (*fiber laser*) is mounted just above the array. Its light is guided via optical fibers of equal length to each OM pair. The fiber laser provides the OMs with simultaneous light signals in order to determine the offset for each channel. The second laser (*water laser*) is arranged 20 m below the array. Its light propagates through the water. This laser serves to monitor the water quality, in addition to dedicated environmental devices located along a separate string. A full cycle of detector calibration running both lasers over a wide range of intensities is repeated every third day.

The upgraded telescope NT200+ was put into operation on April 9th, 2005 [3]. This configuration consists of the old NT200 telescope, surrounded by three new external strings (see Fig.1). The external strings are 140 m long and are placed at 100 meter distance from the center of NT200. Each string contains 12 OMs grouped in pairs like in NT200. The upper pairs are at approximately the same level as the

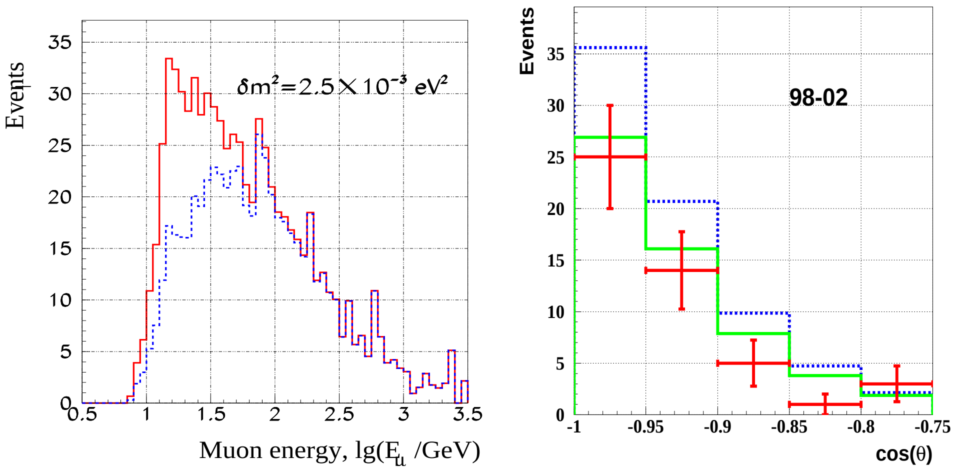

Fig. 2. Left: Energy distribution of muons produced by atmospheric neutrinos, after cuts. Dashed/full histogram include/neglect oscillations. Right: Angular distributions of selected neutrino candidates as well as expected distributions in case of and without oscillations (solid and dashed curves respectively).

bottom OMs of NT200. For NT200+, calibration is done with a powerful external laser light source with up to 5×10^{13} photons per pulse and nsec-pulse duration, which is located between two outer strings, see Fig.1.

Our earlier limits on muon flux induced by WIMPs annihilation at the center of the Earth, which have been obtained with NT200 using data collected during 1998-1999, were presented elsewhere [4]. Here we present the new results of a search for nearly vertically upward going neutrino-induced muons with 1038 live days data from detector NT200 taken over the five year period 1998-2002.

2. Search for Neutrinos from WIMP Annihilation

The search for WIMPs with the Baikal neutrino telescope is based on a possible signal of nearly vertically upward going muons, exceeding the flux of atmospheric neutrinos. 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. The cuts remove muon events far away from the opposite zenith as well as background events which are mostly due to pair and bremsstrahlung showers below the array and to bare downward moving atmospheric muons with zenith angles close to the horizon ($\theta > 60°$). 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 $\geq$5 hit channels, out of which $\geq$4 hits are along at least one of all hit strings. To this sample, a series of 5 cuts is applied. Firstly, the time differences of hit channels along each individual string have to be compatible with a particle close to the opposite zenith (1). The event length should be large enough (2), and the center of gravity of hit channels should not be close to the detector bottom (3). The latter two cuts reject efficiently brems showers from downward muons. Finally, also time differences of hits along *different* strings have to correspond to a nearly vertical muon (cuts 4 and 5).

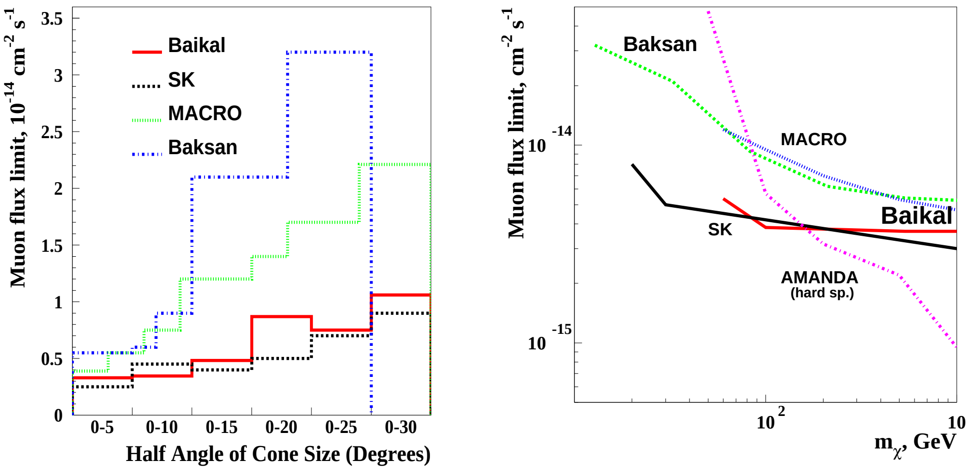

Fig. 3. Left: Limits on the excess muon flux from the center of the Earth versus half-cone of the search angle. Right: Limits on the excess muon flux from the center of the Earth as a function of WIMP mass.

Fig. 1 (right panel) shows the dependence of the detection area on the cosine of the zenith angle θ. The applied cuts select muons with -1< cos(θ) <-0.65 and result in a detection area of about 1800 m^2 for vertically upward going muons.

The expected (normalized) energy spectrum of muons produced by atmospheric neutrinos (Bartol flux [5]), which survive all cuts, with oscillations (using Super-Kamiokande parameter set $\delta m^2 = 2.5 \cdot 10^{-3}$ eV^2 with full mixing, $\theta_m \approx \pi/4$ [6]) and without oscillations is shown in Fig. 2 (left panel). The energy threshold for this analysis is $E_{\rm thr} \sim 10$ GeV. We expect a muon event suppression of (25-30)% due to neutrino oscillations.

From 1038 days of effective data taking between April 1998 and February 2003, 48 events with -1< cos(θ) <-0.75 have been selected as neutrino candidates, comparing to 56.6 events expected from atmospheric neutrinos in case of oscillations and 73.1 without oscillations. The angular distribution of these events as well as the MC - predicted distributions without (dashed curve) and with (solid curve) oscillations are shown in Fig. 2 (right panel). Within 1σ statistical uncertainties the experimental angular distribution is consistent with the prediction including neutrino oscillations. Note, also, that the theoretical uncertainty in the atmospheric neutrino flux calculation is estimated to be about 20% [7].

2.1. *Limit on muon excess from WIMP annihilation*

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. The 90% C.L. muon flux limits for six cones around the opposite zenith obtained with NT200 ($E_{\rm thr}$ >10 GeV) in 1998-2002 are shown in Fig. 3 (left panel). It was shown [8–10] that the size of a cone which contains 90% of signal strongly depends on neutralino mass. The 90% C.L. flux limits are calculated as a function of neutralino mass using cones which collect 90% of the expected signal [8] and are corrected for the 90% collection efficiency due to cone size. These limits are shown in Fig. 3 (right panel). Also shown in Fig. 3 are limits obtained by Baksan [8], MACRO [9], Super-Kamiokande [10] and AMANDA [11].

3. Conclusion

The Baikal neutrino telescope NT200 is taking data since April 1998. A search has been performed for nearly vertically upward going muons based on NT200 telescope data from the five years 1998-2002. The number of detected events, as well as their angular distribution, is compatible with expectation from atmospheric neutrinos. No statistically significant excess of nearly vertically upward going muons over atmospheric neutrino background was seen.

Limits on an excess of the muon flux due to WIMP annihilation in the center of the Earth for various cone angles around nadir as well as muon flux limits for different neutralino masses have been derived, and compared with previous estimates by other experiments.

Acknowledgments

This work was supported by the Russian Ministry of Education and Science, the German Ministry of Education and Research and the Russian Fund of Basic Research (grants 05-02-17476, 04-02-17289, 04-02-16171, 05-02-16593, 06-02-31012, 06-02-31005), by the Grant of the President of Russia NSh-4580.2006.2 and by NATO-Grant NIG-9811707 (2005).

References

[1] I. Belolaptikov *et al.* Astropart. Phys. **7**, 263, 1997.

[2] R. I. Bagduev *et al.* Nucl. Instr. and Meth. **A420**, 138, 1999.

[3] V. Aynutdinov *et al.* Nucl. Instr. and Meth. **A567**, 433, 2006; arXiv.org: astro-ph/0609743.

[4] V. Aynutdinov *et al.* Nucl. Phys. (Proc. Suppl.) **B143**, 335, 2005.

[5] V. Agrawal *et al.* Phys. Rev. **D53**, 1314, 1996.

[6] A. Habig *et al.* Proc.of the XVIII ICRC, 1255, 2003.

[7] T. Gaisser and M. Honda Ann. Rev. Nucl. Part. Sci. **D53**, 153, 2002.

[8] M. M. Boliev *et al.* Nucl. Phys. (Proc. Suppl.) **48**, 83, 1996; O. Suvorova arXiv.org: hep-ph/9911415, 1999.

[9] M. Ambrosio *et al.* Phys. Rev. **D60**, 082002, 1999.

[10] S. Desai *et al.* Phys. Rev. **D70**, 083523, 2004.

[11] A. Achterberg *et al.* Astropart. Phys. **26**, 129, 2006.