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Registration of atmospheric neutrinos with the BAIKAL Neutrino Telescopes

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Abstract

We present neutrino induced events observed with a deep underwater neutrino telescope. Data from 70 days effective life time of the BAIKAL prototype telescope NT-96 have been analyzed with two different methods. With the standard track reconstruction method, 9 clear upward muon candidates have been identified, in good agreement with expectation from Monte Carlo calculations for atmospheric neutrinos. The second analysis is tailored to muons coming from close to the opposite zenith. It yields 4 events, compared to 3.5 from Monte Carlo expectations. From this we derive a 90% upper flux limit of $1.1 \cdot 10^{-13}$ cm^{-2} sec^{-1} for muons in excess of those expected from atmospheric neutrinos with zenith angle $>$ 150 degrees and energy $>$ 10 GeV.

1 Introduction:

The ultimate goal of large underwater neutrino telescopes is the identification of extraterrestrial neutrinos of high energies. The omnipresent background with respect to these neutrinos are neutrinos generated by cosmic ray interactions in the atmosphere of the Earth. While being a background with respect to extraterrestrial neutrinos, atmospheric neutrinos can be used as a standard signal to demonstrate the feasibility of underwater neutrino detectors. Therefore, the primary challenge for these detectors is the identification of upward muons generated in interactions of atmospheric neutrinos. Taking into account that the flux of downward muons at 1 km depth is about 6 orders of magnitude larger than the flux of upward muons from atmospheric neutrinos, this task is far from being trivial (Belolaptikov et al. 1997).

The present paper describes the method for full spatial reconstruction of muon tracks with the four-string array NT-96 in Lake Baikal, and the criteria to reject fake events from misreconstructed downward muons. We present results from the analysis of 70 days effective lifetime of NT-96.

In contrast to the standard reconstruction strategy, which supposes $\geq$6 hits at $\geq$3 of the vertical strings, the second analysis is performed also for events with hits along less than 3 strings. This considerably increases the effective area in vertical direction. Instead of beginning with a reconstruction and then applying quality cuts, we start with cuts effectively rejecting all events with the exception of nearly vertically upward moving muons. An excess of such muons over the expectation value for muons from atmospheric neutrinos could indicate neutrino production by the annihilation of neutralinos – the favoured supersymmetric candidate for cold dark matter – in the center of the Earth. By a method of that kind, two first neutrino events have been identified in NT-36, the very first small BAIKAL prototype array (Balkanov et al., 1997). In the second part of this paper, we apply this strategy to NT-96 data and derive an upper limit on the excess muons from the center of the Earth.

The detector NT-96 installed 1996 at the Lake Baikal consists of 96 photomultipliers (48 information channels) deployed at four strings which are arranged at the edges of a trapezoid with sides length of 3 × 18.5 m and 10.5 m. Each string has a length 70 meters.

2 Selection of neutrino events over a large solid angle

The reconstruction algorithm is based on the assumption that the light radiated by the muons is emitted exactly under the Cherenkov angle (42 degrees) with respect to the muon path. This ”naked muon model” is

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[1] for a full auther list, see talk of L.A.Kuzmichov (26^{th} ICRC HE 4.2.04)

a simplification, since the direction of shower particles accompanying the muons is smeared around the muon direction. Atmospheric muons may occur in bundles. Also, light may be *scattered* on its way.

The reconstruction procedure consists of the following steps:

1. A first quality analysis of the event which *a)* excludes events far from being described by the model of a ”naked muon”, and *b)* finds a first guess for the χ^2 minimization.
2. Determination of the muon trajectory based on the minimization of the function

$$\chi_t^2 = \sum_{i=1}^{N_{hit}} (T_i(\theta, \phi, u_0, v_0, t_0) - t_i)^2 / \sigma_{ti}^2 \tag{1}$$

   Here, t_i are the measured times and T_i the times expected for a given set of track parameters. N_{hit} is the number of hit channels, σ_{ti} are the timing errors. A set of parameters defining a straight track is given by θ and ϕ – zenith and azimuth angle of the track, respectively, u_0 and v_0 – the two coordinates of the track point closest to the center of the detector, and t_0 – the time the muon passes this point.
3. Rejection of most bad reconstructed events with the help of final quality criteria.

Seventy percent of the triggered events (trigger *6/3*, meaning at least 6 hits at 3 strings.) pass these criteria in both the experimental and the MC sample. In the case of MC generated neutrino induced muons, the rate is larger (80%) due to the absence of muon bundles.

We apply *final* quality cuts after the minimization (see item 3 above). For *NT-96* the most effective cuts are the traditional χ^2 cut, cuts on the probability of non-fired channels not to be hit, and fired channels to be hit (P_{nohit} and P_{hit}, respectively), cuts on the correlation function of measured amplitudes to the amplitudes expected for the reconstructed tracks, and a cut on the amplitude χ^2 defined similar to the time χ^2 defined above.

To guarantee a minimum lever arm for track fitting, we reject events with a projection of the most distant channels on the track (Z_{dist}) below 35 meters. Due to the small transversal dimensions of *NT-96*, this cut excludes zenith angles close to the horizon, i.e., the effective area of the detector with respect to atmospheric neutrinos is decreased considerably (fig.1). Rejection of all events with less than 9 hits results in a small decrease of the detector sensitivity for neutrino events, but reduces the background by a factor of 4.

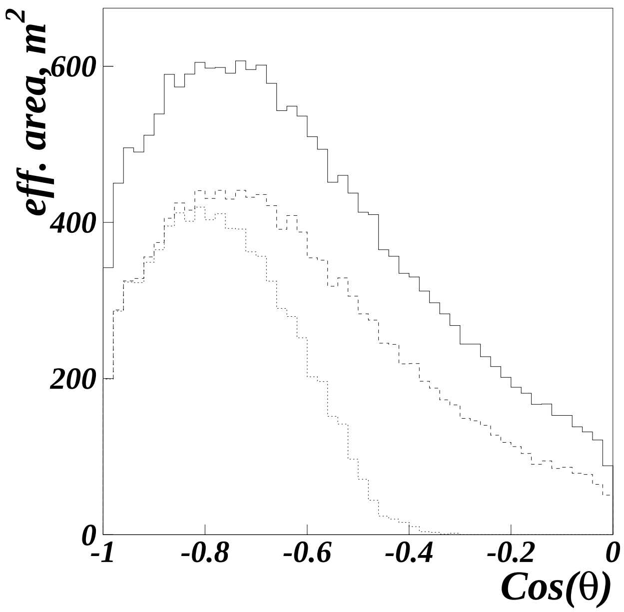

Figure 1: Effective area for upward MC muons satisfying trigger *9/3*. Solid line - no quality cuts, dashed line - all quality cuts, dotted line - all quality cuts and cut on Z_{dist} (see text). θ is the MC generated zenith angle.

The efficiency of the procedure has been tested with a sample of $1.8 \cdot 10^6$ MC-generated atmospheric muons, and with MC-generated upward muons due to atmospheric neutrinos. It turns out that the signal to noise ratio is > 1 for this sample.

We have reconstructed $2 \cdot 10^7$ events taken with *NT-96* in April/September 1996 (70.3 days). Nine of them were reconstructed as upward going muons, passed all quality cuts and triggered at least 9 channels at 3 strings. This is in good agreement with MC expectations. The resulting angular distribution is presented in fig.2.

Table 1: The expected number of atmospheric neutrino events and background events, and the observed number of events after cuts *1–6*.

	after cut N^o					
	1	2	3	4	5	6
atm. ν, MC	11.2	5.5	4.9	4.1	3.8	3.5
background, MC	7106	56	41	16	1.1	0.2
experiment	8608	87	66	28	5	4

3 Identification of nearly vertically upward moving muons

Different to the standard analysis (Belolaptikov et al. 1997), the method presented in this section relies on the application of a series of cuts which are tailored to the response of the telescope to nearly vertically upward moving muons (Bezrukov et al. 1995, Balkanov et al. 1998). 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 naked 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 the zenith angle.

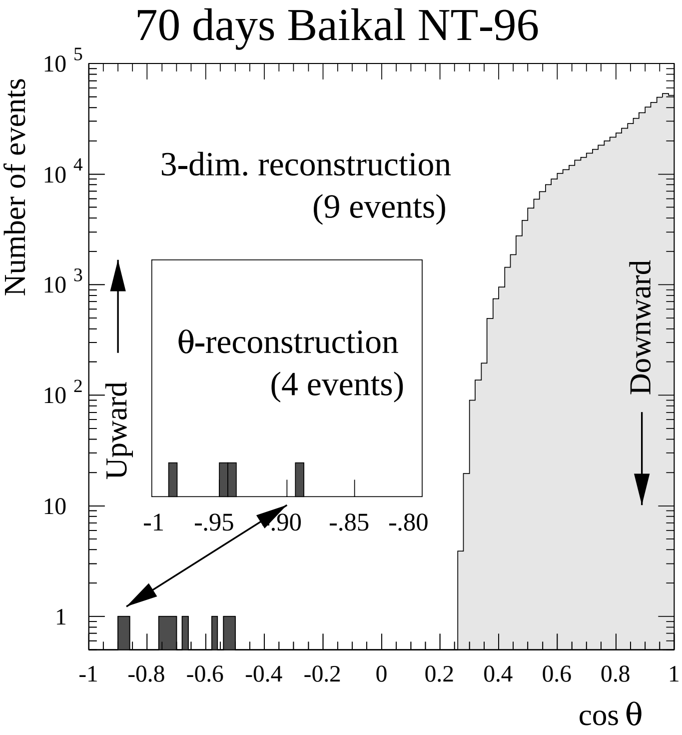

Figure 2: Experimental angular distribution of events satisfying trigger *9/3*, all final quality cuts and the limit on Z_{dist} (see text). The subpicture shows the events selected by using the method described in section 3. The event found by both algorithms is marked by the arrow.

We included all events with $\geq$4 hits along at least one of all hit strings. To this sample, a series of 6 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), the maximum recorded amplitude should not exceed a certain value (3) and the center of gravity of hit channels should not be close to the detector bottom (4). 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 (5) and the time difference between top and bottom hit in an event has to be larger than a minimum value (6).

The effective area for muons moving close to opposite zenith and fulfilling all cuts exceeds $1000\ \mathrm{m}^2$.

Within 70 days of effective data taking, $8.4 \cdot 10^7$ events with the muon trigger $N_{hit} \geq 4$ have been selected.

Table 1 summarizes the number of events from all 3 event samples (MC signal and background, and experiment) which survive the subsequent cuts. After applying all cuts, four events were selected as neutrino candidates, compared to 3.5 expected from MC. One of the four events has 19 hit channels on four strings and was selected as neutrino candidate by the standard analysis too. The zenith angular distribution of these four neutrino candidates is shown in the inner box of fig.2.

Regarding the four detected events as being due to atmospheric neutrinos, one can derive the upper limit on

Table 2: 90% C.L. upper limits on the muon flux from the center of the Earth for four regions of zenith angles obtained in different experiments

Zenith angles	Flux limit ($10^{-14} \cdot (cm^2\ sec)^{-1}$)			
	NT-96 $> 10GeV$	*Baksan* $> 1GeV$	*MACRO* $> 1.5GeV$	*Kam-de* $> 3GeV$
$\geq 150°$	11.0	2.1	2.67	4.0
$\geq 155°$	9.3	3.2	2.14	4.8
$\geq 160°$	$5.9 - 7.7$	2.4	1.72	3.4
$\geq 165°$	4.8	1.6	1.44	3.3

the flux of muons from the center of the Earth due to an annihilation of neutralinos – the favored candidate for cold dark matter.

The limits on the excess muon flux obtained with underground experiments (Boliev et al. 1996, Montaruli et al. 1997, Mori et al. 1993) and *NT-96* are shown in Table 2. The limits obtained with *NT-96* are 4–7 times worse then the best underground limits since the data collecting time of *NT-96* was only ≈ 70 days.

This result, however, illustrates the capability of underwater experiments with respect to the search for muons due to neutralino annihilation in the center of the Earth.

4 Conclusions

Twelve neutrino candidates have been separated during 70 days effective lifetime of the four-string detector *NT-96* in Lake Baikal. Nine of them have hits at ≥ 3 strings and are fully reconstructed. The other three events have hits at 2 strings and have direction close to the opposite zenith. The observed numbers for both separation methods is in a good comparision with expected ones.

Also the limit on the flux of neutrinos from WIMP annihilation in the center of the Earth have been derived.

At present, the *NT-200* telescope (Sokalski & Spiering, 1992, Balkanov et al. 1999) is taking data. It contains twice the number of optical modules as *NT-96*. From the fully operational *NT-200* array, 1–2 neutrino events per two days are going to be separated.

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