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A search for very high energy neutrinos with the Baikal Neutrino Telescope

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Abstract. We present the results of a search for high energy neutrinos with the Baikal underwater Cherenkov detector *NT-200*. An upper limit on the $(\nu_e + \tilde{\nu_e})$ diffuse flux of $E^2\Phi_\nu(E) < (1.3 \div 1.9) \cdot 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ GeV within a neutrino energy range $10^4 \div 10^7$ GeV is obtained, assuming an E^{-2} behaviour of the neutrino spectrum and flavor ratio $(\nu_e + \tilde{\nu_e}) : (\nu_\mu + \tilde{\nu_\mu})$=1:2.

1 Introduction

The Baikal Neutrino Telescope is deployed in Lake Baikal, Siberia, 3.6 km from shore at a depth of 1.1 km. The optical properties of Lake Baikal deep water are characterized by an absorption length of 20$\div$ 25 m, a scattering length of 20$\div$70 m and a strongly anisotropic scattering function $f(\theta)$ with mean cosine of scattering angle $\overline{\cos}(\theta)$=0.85$\div$0.95. *NT-200*, the medium-term goal of the collaboration (Belolaptikov et al., 1997), was put into operation on April 6th, 1998. See (Balkanov et al. these proceedings) for the BAIKAL experiment status review. Here we present preliminary results from a search for high energy neutrinos (E_ν >10 TeV) with *NT-200* obtained from the analysis of the entire 1998 data set.

2 A search for high energy neutrinos

The main goal of large underwater neutrino telescopes is the search for extraterrestrial high energy neutrinos. Detection volume and detection area of such detectors depend on the transparency of the medium (water or ice) and the power of the source of Cherenkov radiation (high energy shower or muon), and may significantly exceed the geometrical one.

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2.1 Search strategy

The used search strategy for high energy neutrinos relies on the detection of the Cherenkov light emitted by the electromagnetic and (or) hadronic particle cascades and high energy muons produced at the neutrino interaction vertex in a large volume around the neutrino telescope. Earlier, a similar strategy has been used by DUMAND (Bolesta et al., 1997), AMANDA (Porrata et al., 1997) and BAIKAL (Balkanov et al., 2000) collaborations to obtain upper limits on the diffuse flux of high energy neutrinos with relatively small detectors (SPS, AMANDA-A and *NT-96*, respectively). Although the limits implied by these observations are at least one order of magnitude higher then the model independent upper limit derived from the energy density of the diffuse X- and gamma-radiation (Berezinsky et al., 1990), these results illustrate the power of used search strategy.

Neutrinos produce showers through CC(NC)-interactions with nucleons as well as through resonance production

$$\bar{\nu_e} + e^- \rightarrow W^- \rightarrow \text{anything}, \tag{1}$$

with the resonant neutrino energy $E_0 = M_w^2/2m_e = 6.3 \cdot 10^6$ GeV and cross section $5.02 \cdot 10^{-31}\mathrm{cm}^2$.

We select events with high multiplicity of hit channels N_{hit} corresponding to bright cascades. The volume considered for generation of cascades is essentially *below* the geo-

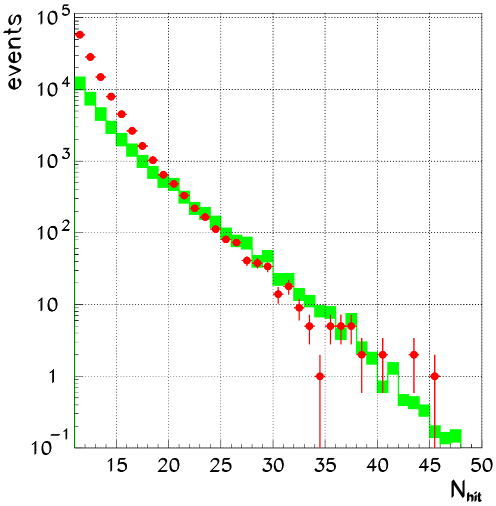

Fig. 1. Distribution of hit channels multiplicity; dots - experiment, hatched boxes - expectation from brems and hadronic showers produced by atmospheric muons.

metrical volume of *NT-200*. A cut is applied which accepts only time patterns corresponding to upward traveling light signals (see below). This cut rejects most events from brems-cascades produced by downward going muons since the majority of muons is close to the vertical; they would cross the detector and generate a downward time pattern. Only the fewer muons with large zenith angles may escape detection and illuminate the array by their proper Cherenkov radiation or via bright cascades from below the detector. These events then have to be rejected by a stringent multiplicity cut.

The used strategy is very effective for ν_e and ν_τ detection since the main fraction of neutrino energy would be transfered to electro-magnetic or/and hadronic cascades due to CC-interactions. It is less effective for ν_μ detection since the main part of neutrino energy would be escaped by energetic muon from detection volume. For ν_μ search preliminary result has been presented by the AMANDA experiment (Andres et al., 2001).

2.2 Data

Within the 234 days of the detector livetime, $1.67 \cdot 10^8$ events with $N_{hit} \geq 4$ have been selected. For this analysis we used events with $N_{hit} > 10$. The time difference between any two hit channels on the same string was required to obey the condition:

$$(t_i - t_j) > -10 \text{ ns}, \quad (i < j), \tag{2}$$

where t_i, t_j are the arrival times at channels i, j and the numbering of channels rises from top to bottom along the string.

Since April 1998 till February 1999, *NT-200* operated in 3 main configurations with 77, 60 and 49 working channels, respectively. Data taking time T, the number of selected events N_{ev} which survive cut (2) and the maximum hit multiplicity N_{hit}^{max} of these events. are shown in Table 1.

Table 1. *NT-200* configurations in 1998.

Configuration	N_{op}	T (days)	N_{ev}	N_{hit}^{max}	N_{thr}
1	77	57.9	63540	45	50
2	60	145.8	83319	37	39
3	49	30.9	8719	24	26

Fig.1 shows the hit multiplicity distribution of selected (dots) as well as the expected one from background high energy brems and hadronic showers produced by atmospheric muons (hatched boxes). The experimental distribution is consistent with the theoretical expectation for $N_{hit} > 18$. For lower N_{hit} values the contribution of atmospheric muons close to horizon as well as low energy showers from e^+e^- pair production become important. The highest multiplicity of hit channels experimentally observed is $N_{hit}^{max} = 45$ (one event). No statistically significant excess over expectation from atmospheric muon induced showers has been observed for each of the 3 detector configurations. The detection efficiency of *NT-200* for events with $N_{hit} > N_{hit}^{max}$ had been analyzed by applying several less stringent cuts. It was shown that the experimental N_{hit} distributions are consistent with expected ones from atmospheric muons.

Since no events with $N_{hit} > N_{hit}^{max}$ are found in our data we can derive upper limits on the flux of high energy neutrinos which would produce events with

$$N_{hit} > N_{thr}, \tag{3}$$

where the chosen values of N_{thr} for the 3 detector configurations are given in Table 1.

2.3 MC-simulations

Given an isotropic diffuse high energy neutrino flux with power law energy spectrum with spectral index γ, the number of expected events during observation time T reads

$$N_\nu = \frac{A_\nu T}{4\pi} \int d\Omega \int dE V_{eff}(\Omega, E) \sum_k \int dE_\nu E_\nu^{-\gamma} N_A \times$$

$$\rho_{H_2O} \frac{d\sigma_{\nu k}}{dE} \exp(-l(\Omega)/l_{tot}) \tag{4}$$

where E_ν is the neutrino energy, E - the energy transferred to a shower, A_ν - normalization coefficient of neutrino flux and $V_{eff}(\Omega, E)$ - detection volume [1]. The index ν indicates neutrino types ($\nu = \nu_\mu, \tilde{\nu_\mu}, \nu_e, \tilde{\nu_e}$) and k indicates the summation over CC and NC interactions. N_A is the Avogadro number. Cross sections (Berezinsky et al., 1986; Gandhi et al., 1996) $d\sigma_{\nu k}/dE$ correspond to neutrino-nucleon interactions.

[1]In a case of ν_μ CC- interaction in water the detector response to hadronic shower as well as to the high energy muon has been taken into account.

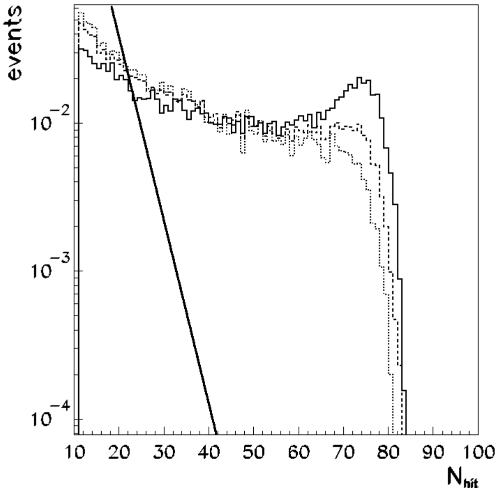

Fig. 2. The normalized hit multiplicity distributions of events which would be produced by the ν_e fluxes and survive the selection criterion (2). Solid, dashed and dotted curves correspond to γ=1.5, 2, 2.5, respectively. Also shown is the normalized N_{hit} distribution of events from atmospheric muon induced showers (thick line).

The neutrino absorption in the Earth has been taken into account with a suppression factor $\exp(-l(\Omega)/l_{tot})$, where $l(\Omega)$ is the neutrino path length through the Earth in direction Ω and $l_{tot}^{-1} = N_A\,\rho_{Earth}\,(\sigma_{CC} + \sigma_{NC})$ according to (Berezinsky et al., 1986; Gandhi et al., 1996).

In Fig.2 we show the normalized predictions of N_{hit} distributions of events which survive cut (2) and would be induced by electron neutrino fluxes with γ=1.5, 2, 2.5. The normalized N_{hit} distribution of events from atmospheric muon induced showers, which has strongly steeper behaviour, is also presented.

The detection volume for neutrino produced events which fulfill conditions (2)-(3) was calculated as a function of neutrino energy and zenith angle θ. The energy dependence of the detection volume for isotropic ν_e flux with γ =2 is shown in Fig.3. Also shown is the detection volume folded with the neutrino absorption probability in the Earth. The value of V_{eff} rises from $2{\cdot}10^5$ m^3 for 10 TeV up to $6{\cdot}10^6$ m^3 for 10^4 TeV and significantly exceeds the geometrical volume $V_g \approx 10^5$ m^3 of *NT-200*. This is due to the low light scattering and the preserved light fronts from Cherenkov waves originating far outside the geometrical volume. Although the detection volume has been calculated without taking into account light scattering in the water, estimations show that a scattering with L_s=20 m and $\overline{\cos}(\theta)$=0.88 (conservative values for Lake Baikal water) would cause $\leq$30% decrease of V_{eff} for $E_\nu \leq 10^3$TeV.

Fig.4 illustrates the difference between V_{eff} and V_g. Shown here are the coordinates of neutrino interaction vertex for events which survive cuts (2) (dots) and (2)-(3) (rectangles).

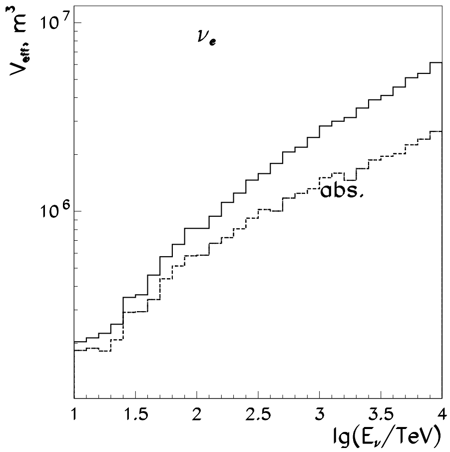

Fig. 3. Detection volume of ν_e produced events which survive cuts (2)-(3) (upper curve). The detection volume folded with the neutrino absorption probability in the Earth (lower curve) is also shown.

2.4 The limits on the high energy neutrino fluxes

The shape of the neutrino spectrum was assumed to behave like E^{-2} and flavor ratio $(\nu_e + \tilde{\nu_e}) : (\nu_\mu + \tilde{\nu_\mu}) = 1 : 2$ due to photo-meson production of π^+ followed by the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \tilde{\nu_\mu} + \nu_\mu$ for extraterrestrial sources.

Comparing the expected number of events fulfilling (2)-(3) with the upper limit on the actual number of events, 2.4 for 90% C.L. (Feldman and Cousins, 1998) we obtain the upper limit on the diffuse $(\nu_e + \tilde{\nu_e})$ flux. The combined upper limit obtained with Baikal neutrino telescopes *NT-200* (234 days) and *NT-96* (Balkanov et al., 2000) (70 days) is:

$$\Phi_{(\nu_e+\tilde{\nu_e})} E^2 < (1.3 \div 1.9)\cdot 10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}, \qquad (5)$$

where the upper value refers to the conservative limit on light scattering in the Baikal water.

Fig.5 shows the upper limits on the isotropic diffuse high energy neutrino fluxes obtained by BAIKAL (this work), AMANDA (Andres et al., 2001) and FREJUS (Rhode et al., 1994) (triangle) experiments as well as the atmospheric conventional neutrino fluxes (Volkova, 1980) from horizontal and vertical directions (upper and lower curves, respectively) and atmospheric prompt neutrino flux (Thunman et al., 1996) (curve labeled ν_{pr}). Also shown is the model independent upper limit on the diffuse high energy neutrino flux obtained by V.Berezinsky (Berezinsky et al., 1990) (curve labeled 'B') with the energy density of the diffuse X- and gamma-radiation $\omega_x \leq 2\cdot 10^{-6}$ eV cm^{-3} (as follows from EGRET data (Sreekumar et al., 1998)), and predictions for diffuse neutrino fluxes from Stecker and Salamon model (Stecker and Salamon, 1995) (the sum of the quasar core and blazar jet contribution, curve labeled 'SS') and Protheroe model (Protheroe, 1997) (from equal contribution from pp and $p\gamma$ interactions in AGN jets, curve labeled 'P'). Curves labeled 'MPR' and 'WB' show the upper bounds obtained by Rachen,

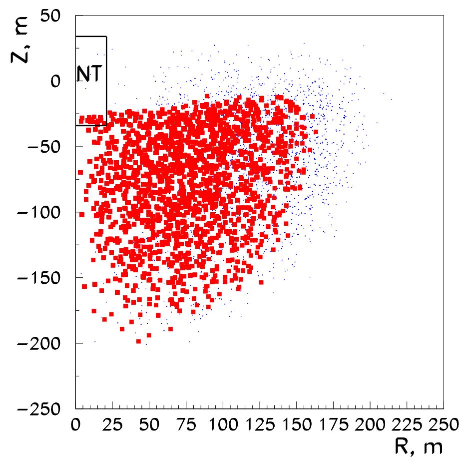

Fig. 4. Coordinates of ν_e interaction vertex for events which fulfill conditions (2) (dots) and (2)-(3) (rectangles).

Mannheim, and Protheroe (Mannheim et al., 1998) for optically thick ($\tau_{n\gamma} > 1$) and optically thin ($\tau_{n\gamma} < 1$) sources as well as the upper bound obtained by Waxman and Bahcall (Waxman and Bahcall, 1999) for optically thin sources respectively. Curves labeled 'M(GRB)' and 'WB(GRB)' present the upper bounds for diffuse neutrino flux from GRBs derived by Mannheim (Mannheim, 2000) and Waxman and Bahcall (Waxman and Bahcall, 1997). Curve labeled 'TD' shows prediction for neutrino flux from topological defects due to specific top-down scenario BHS1 (Bhattacharjee et al., 1992).

Our combined 90% C.L. limit obtained with *NT-200* and *NT-96* (Balkanov et al., 2000) at the W - resonance energy is:

$$\frac{d\Phi_{\bar{\nu}}}{dE_{\bar{\nu}}} \leq (1.4 \div 1.9) \times 10^{-19} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}. \qquad (6)$$

and is also depicted in Fig.5 (rectangle).

3 Conclusion

The deep underwater neutrino telescope *NT-200* in Lake Baikal is taking data since April 1998. Due to the high water transparency and low light scattering, the detection volume of *NT-200* for high energy ν_e and ν_τ detection is several megatons and exceeds the geometrical volume by factor of about 50 for highest energies. This permits a search for diffuse neutrino fluxes from extraterrestrial sources on the level of theoretical predictions. The upper limits (5), (6) obtained for the diffuse E^{-2} ($\nu_e + \tilde{\nu_e}$) flux and the model independent $\tilde{\nu_e}$ flux at resonant energy $6.3 \cdot 10^6$GeV are the most stringent ones at present. We expect that the analysis of 3 years data taken with *NT-200* would allow us to reach a sensitivity of $\Phi_\nu E^2 \approx 6 \cdot 10^{-7} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}$.

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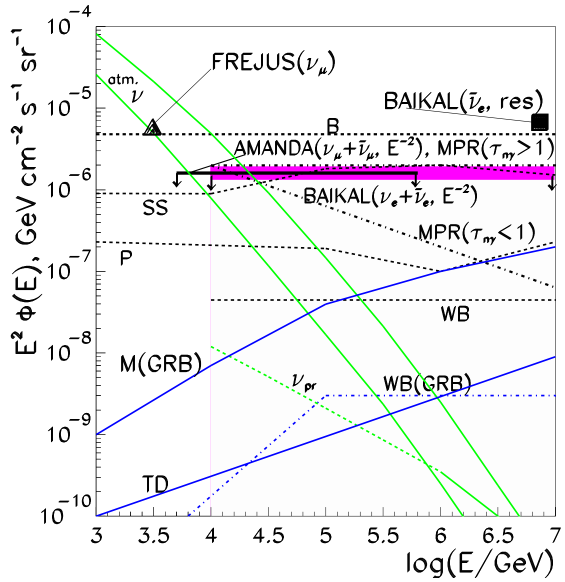

Fig. 5. The experimental upper limits on the neutrino fluxes as well as flux predictions in different models of neutrino sources (see text).

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