Search for a diffuse flux of high-energy neutrinos with the Baikal neutrino telescope NT200

A. Avrorin[*], V. Aynutdinov[*], V. Balkanov[*], I. Belolaptikov[§], D. Bogorodsky[†], N. Budnev[†], I. Danilchenko[*], G. Domogatsky[*], A. Doroshenko[*], A. Dyachok[†], Zh.-A. Dzhilkibaev[*], S. Fialkovsky[‖], O. Gaponenko[*], K. Golubkov[§], O. Gress[†], T. Gress[†], O. Grishin[†], A. Klabukov[*], A. Klimov[††], A. Kochanov[†], K. Konischev[§], A. Koshechkin[*], V. Kulepov[‖], D. Kuleshov[*], L. Kuzmichev[‡], V. Lyashuk[*], E. Middell[¶], S. Mikheyev[*], M. Milenin[‖], R. Mirgazov[†], E. Osipova[‡], G. Pan'kov[†], L. Pan'kov[†], A. Panfilov[*], D. Petukhov[*], E. Pliskovsky[§], P. Pokhil[*], V. Poleschuk[*], E. Popova[‡], V. Prosin[‡], M. Rozanov[**], V. Rubtzov[†], A. Sheifler[*], A. Shirokov[‡], B. Shoibonov[§], Ch. Spiering[¶], O. Suvorova[*], B. Tarashansky[†], R. Wischnewski[¶], I. Yashin[‡], V. Zhukov[*]

[*]*Institute for Nuclear Research of Russian Academy of Sciences,*
117312, Moscow, 60-th October Anniversary pr. 7a, Russia
[†]*Irkutsk State University, Russia*
[‡]*Skobeltsyn Instutute of Nuclear Physics MSU, Moscow, Russia*
[§]*Joint Institute for Nuclear Research, Dubna, Russia*
[¶]*DESY, Zeuthen, Germany*
[‖]*Nizhni Novgorod State Technical University, Nizhnij Novgorod, Russia*
[**]*St.Petersburg State Marine University, St.Petersburg, Russia*
[††]*Kurchatov Institute, Moscow, Russia*

Abstract. **We present the results of a new analysis of data taken in 1998-2002 for a search for high-energy extraterrestrial neutrinos. The analysis is based on a full reconstruction of high-energy cascade parameters: vertex coordinates, energy and arrival direction. Upper limits on the diffuse fluxes of all neutrino flavors, predicted by several models of AGN-like neutrino sources are derived. For an $\mathbf{E^{-2}}$ behavior of the neutrino spectrum, our limit is $\mathbf{E^2F_\nu(E) < 2.9 \times 10^{-7}}$ $\mathbf{cm^{-2}}$ $\mathbf{s^{-1}}$ $\mathbf{sr^{-1}}$ GeV over a neutrino energy range $\mathbf{2 \times 10^4 \div 2 \times 10^7}$ GeV. This limit is by a factor of 2.8 more stringent than a limit obtained with a previous analysis.**

***Keywords*: high-energy neutrinos, neutrino telescopes, Baikal**

I. INTRODUCTION

High-energy neutrinos are likely produced in violent processes in the Universe. Many theoretical models predict that neutrinos are generated by hadronic processes within high energy astrophysical sources such as active galactic nuclei (AGN), supernova remnants or gamma ray bursts. Individual sources might be too weak to produce an unambiguous directional signal, however the total neutrino flux from all sources could produce a detectable diffuse neutrino signal. Astrophysical neutrinos generated in top-down models are, by definition, of diffuse nature. To date the highest sensitivities to diffuse neutrino fluxes in a range 10 TeV $\div$ 100 PeV are achieved with the NT200(Baikal) [1] and AMANDA [2], [3] neutrino telescopes.

The Baikal Neutrino Telescope NT200 is operating in Lake Baikal at a depth of 1.1 km and is taking data since 1998. Since 2005, the upgraded 10-Mton scale detector NT200+ is in operation. Detector configuration and performance have been described elsewhere [4], [5], [6], [7]. Due to high water transparency and low light scattering, the detection volume of NT200 for high energy ν_e, ν_μ and ν_τ events significantly exceeds the instrumented volume. Our previous analysis [1] of 1038 live-days data, collected in the years 1998-2002 with NT200, has allowed to set the limits on diffuse neutrino fluxes predicted by several theoretical models. Here we discuss a new analysis method which is based on an energy and space-angular reconstruction of high-energy cascades and present limits on diffuse neutrino fluxes which are improved by a factor of about three over the previous ones.

II. THE ANALYSIS METHOD

The BAIKAL survey for high energy neutrinos searches for bright cascades produced at the neutrino interaction vertex in a large volume around and below the telescope. The main background source are atmospheric muons, with a flux 10^6 times higher than that of atmospheric neutrinos. 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

TABLE I: Expected number of events N_{model}, detection energy range which contains the central 90% of the expected signal $\Delta E_{90\%}$, median energy of the expected signal $\bar{E_\nu}$, and model rejection factors $\eta = n_{90\%}/N_{model}$ for models of astrophysical neutrino sources.

	BAIKAL				AMANDA
Model	$N_{model}(\nu_e+\nu_\mu+\nu_\tau)$	$\Delta E_{90\%}$	$\bar{E_\nu}$	$n_{90\%}/N_{model}$	$n_{90\%}/N_{model}$
S05	0.7	100 TeV ÷ 30 PeV	2 PeV	3.4	1.6
P $p\gamma$	4.4	320 TeV ÷ 160 PeV	6 PeV	0.5	0.3
M $pp+p\gamma$	1.7	20 TeV ÷ 500 PeV	15 PeV	1.4	1.2
MPR	1.4	160 TeV ÷ 100 PeV	3 PeV	1.8	0.9
SeSi	2.4	1 PeV ÷ 50 PeV	10 PeV	1.0	-

and negative values of $t_{\rm min}$ correspond to upward and downward propagation of light, respectively. We require

$$t_{\rm min} > -10{\rm ns}. \qquad (1)$$

This cut accepts only time patterns corresponding to upward traveling light signals. It rejects most events from brem-cascades produced by downward going muons since the majority of muons is close to the vertical; they would cross the detector or pass nearby and generate a downward time pattern. Only few muons with large zenith angles may escape this cut and illuminate the array by their own Cherenkov radiation or that from bright cascades from below.

The energy spectrum of neutrinos from galactic and cosmological sources or from the decay of topological defects is expected to have a significantly flatter shape than the spectrum of atmospheric muons and neutrinos. This gives rise to different N_{hit} and cascades energy distributions. Results of a search for high-energy neutrinos, based on N_{hit} as a rough indicator of the energy deposited in the effective detection volume were published in [1]. Here we present results of an extended analysis which is based on a full reconstruction of cascades parameters.

A. Cascade parameters reconstruction

We use a two step procedure for cascade parameters reconstruction which is applied to events with ≥ 5 hit channels. At the first step, using the time information of hit channels, the coordinates of the cascade vertex are reconstructed by minimizing

$$\chi^2_t = \frac{1}{(N_{hit}-4)}\sum_{i=1}^{N_{hit}}\frac{(T_i(x,y,z,t_0)-t_i)^2}{\sigma^2_{ti}}. \qquad (2)$$

Here t_i is the time measured by the i-th channel, T_i is the expected arrival time of Cherenkov photons induced by a cascade with $\vec{r}_{sh}(x,y,z)$ coordinates, and σ_{ti} are the timing errors. At the next step, taking into account the found coordinates $\vec{r}_{sh}(x,y,z)$, we reconstruct the cascades energy E_{sh}, as well as zenith and azimuth angles θ and φ of cascade axis by maximizing the likelihood function

$$L_A = \prod_{i=1}^{N_{hit}} p_i(A_i, E_{sh}, \vec{\Omega}_{sh}(\theta,\varphi)). \qquad (3)$$

Here $p_i(A_i, E_{sh}, \vec{\Omega}_{sh}(\theta,\varphi))$ is the probability to detect a signal of amplitude A_i by the i-th hit channel. These probability functions are calculated with taking into account the absorption and scattering of light in water and the relative orientations of optical modules and cascades.

B. High-energy neutrino simulation

The number of expected events during observation time T is

$$N_\nu = T\int d\vec{\Omega}\int dE_{sh}V_{eff}(\vec{\Omega},E_{sh})\sum_k\int N_A\rho_{H_2O}$$
$$\times\frac{d\sigma_{\nu k}}{dE_{sh}}\Phi_\nu(\vec{\Omega},E_\nu,X)dE_\nu, \qquad (4)$$
$$X(\vec{\Omega}) = \int_0^L \rho_{earth}(l)dl,$$

where $\Phi_\nu(\vec{\Omega},E_\nu,X)$ is the flux of high-energy neutrinos with energy E_ν in the vicinity of the detector, $\vec{\Omega}$ – the neutrino direction, $X(\vec{\Omega})$ – the thickness of matter encountered by the neutrino on its passage through the Earth, E_{sh} – the energy of secondary cascades, $V_{eff}(\vec{\Omega},E_{sh})$ – the detection volume. The index ν_i indicates the neutrino type and k =1,2 corresponds to CC- and NC-interactions, respectively. N_A is the Avogadro number and ρ_{H_2O} the water density.

A MC-code is used to solve Eq. (4), with the boundary conditions for neutrino fluxes $\Phi_{\nu_i}(E,0) = A_{\nu_i}f_{\nu_i}(E)$, where $f_{\nu_i}(E)$ is a diffuse AGN-like flux or other predicted UHE neutrino fluxes, and a A_{ν_i} a normalization coefficient. For neutrino interactions we used cross-sections from [8]. The neutrinos are propagated through the Earth assuming the density profile of the Preliminary Reference Earth Model [9]. Although a flavor ratio of ν_e:ν_μ:ν_τ ≈1:2:0 is predicted for generic neutrino fluxes at astrophysical sources, equal fractions of all three neutrino flavors are expected at Earth because of neutrino oscillations. Throughout this paper we assumed a neutrino flavor ratio at Earth of ν_e:ν_μ:ν_τ =1:1:1 and the same shape of energy spectra $f_\nu(E)$ for all neutrino flavors, as well as a flux ratio for neutrino and antineutrino of $\nu/\bar{\nu}$ =1[1].

The detector response to Cherenkov radiation of high energy cascades was simulated taking into account the effects of absorption and scattering of light, as well as

[1]A violation of this assumption (e.g. for neutrino production in $p\gamma$ interactions) has a small influence on the result due to the similarity of ν and $\bar{\nu}$ cross-sections in our energy range.

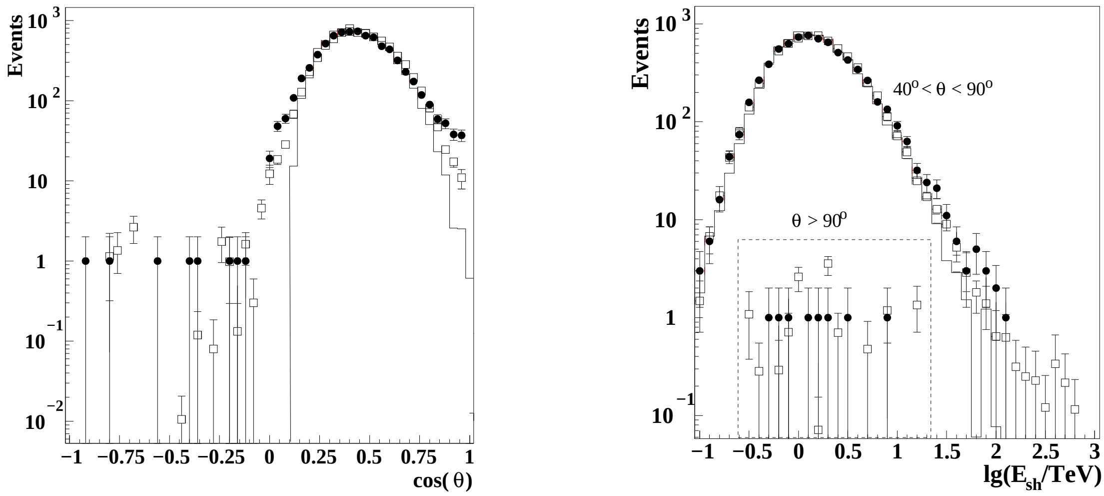

Fig. 1: Left: Reconstructed cascade zenith-angule distribution for data (dots) and for MC-generated atmospheric muons (boxes); true MC zenith-angule distribution is given as histogram. Right: Reconstructed cascade energy distribution for data (dots) and for MC-generated atmospheric muons (boxes); true MC energy distribution is given as histogram.

light velocity dispersion in water. We also implemented the longitudinal development of cascades. For electron cascades with $E_{\rm sh}$ $>2{\times}10^7$ GeV and for hadronic cascades with $E_{\rm sh}$ $>10^9$ GeV, the increase in cascade length due to the LPM effect [10] was approximated as $E^{1/3}$ according to [11].

C. *Atmospheric muon simulation*

Downward going atmospheric muons are the most important source of background. The simulation chain of these muons starts with cosmic ray air shower generation using the CORSIKA program [12] with the QGSJET [13] interaction model and the primary composition and spectral slopes for individual elements taken from [14]. Atmospheric muons are propagated through the water using the MUM program [15]. During passage through the detection volume the detector response to Cherenkov light from all muon energy loss processes is simulated. A total of 1.2×10^9 background events, equivalent to 3671 live days, has been simulated, with standard optical parameters of Baikal water. The cascade reconstruction procedure was applied to simulated background events with N_{hit} >15 which obey the condition (1). To reject events induced by muon bundles the following additional cuts were applied: N_{hit} >18, χ^2_t <3 and $L_A < 20$. Zenith-angule and energy distributions of the selected events are shown in Fig.1 and are discussed in the next section.

III. Results

Within the 1038 days of the detector live time, 3.45×10^8 events with $N_{\rm hit} \geq 4$ have been recorded. For this analysis we used 18384 events with hit channel multiplicity $N_{\rm hit}$ >15 and $t_{\rm min}$ >-10 ns. As it was shown in [1] the data are consistent with simulated background for both $t_{\rm min}$ and $N_{\rm hit}$ distributions.

A full cascade reconstruction algorithm (for vertex, direction, energy) was applied to the data [16]. Cuts were then placed on this reconstructed cascade energy to select neutrino events.

The reconstructed zenith-angule and energy distributions of data are shown in Fig.1 (dots). Eight events were reconstructed as upward going cascades (zenith angle $\theta > 90°$ in the left panel and the distribution in the dashed box in right panel). Also the MC-generated (histograms) and reconstructed (boxes) zenith-angule and energy distributions from simulated atmospheric muons are shown in Fig.1; 12 upward reconstructed cascade-like events are expected. As seen from Fig.1, within systematic and statistical uncertainties there is no significant excess above the background from atmospheric muons. We introduce the following final neutrino signal cuts on the cascade energy: E_{sh} >130 TeV and E_{sh} >10 TeV for downward (40° $< \theta <$90°) and upward going cascades, respectively (see for details [16]). Furthermore, events which fulfil selection requirements used in our previous analysis [1] are also considered as neutrino candidates. With zero observed events and 2.3±1.2 expected background events, a 90% confidence level upper limit on the number of signal events of $n_{90\%}$ =2.4 is obtained.

A model of astrophysical neutrino sources, for which the total number of expected events, N_{model}, is larger than $n_{90\%}$, is ruled out at 90% CL. Table I represents event rates, detection energy range which contains the central 90% of the expected signal, median energy of the expected signal, and model rejection factors (MRF) $n_{90\%}/N_{model}$ for models of astrophysical neutrino sources obtained from our search, as well as model

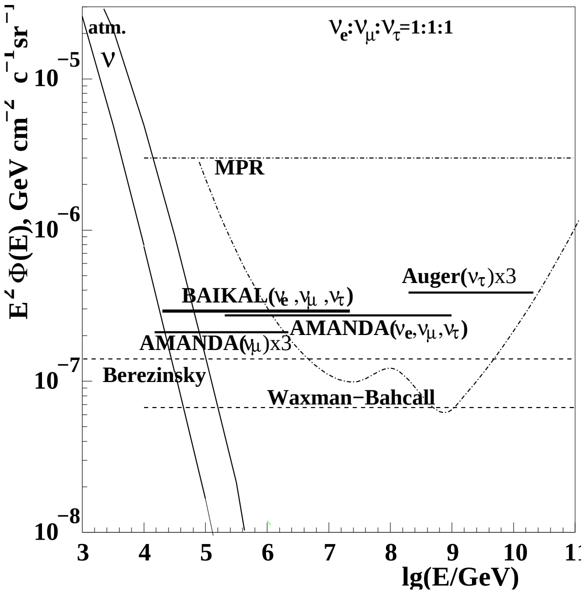

Fig. 2: All-flavor neutrino flux limits and theoretical bounds (see text).

rejection factors obtained recently by the AMANDA collaboration [2], [3]. The model by Stecker [17] labeled "S05", represents models for neutrino production in the central region of Active Galactic Nuclei. Further shown in Table I are models for neutrino production in AGN jets: calculations by Protheroe [18] and by Mannheim [19], which include neutrino production through pp and $p\gamma$ collisions (models "P $p\gamma$" and "M $pp+p\gamma$", respectively), as well as an evaluation of the maximum flux due to a superposition of possible extragalactic sources by Mannheim, Protheroe and Rachen [20] (model "MPR") and a prediction for the diffuse flux from blazars by Semikoz and Sigl [21] "SeSi". As can be seen from Table I the model "P $p\gamma$" is ruled out with $n_{90\%}/N_{model} = 0.5$.

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

$$E^2\Phi < 2.9 \times 10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}, \qquad (5)$$

for $20\,\mathrm{TeV} < \mathrm{E}_\nu < 20\,\mathrm{PeV}$. Fig.2 shows our upper limit on the all-flavor E^{-2} diffuse flux, which is a significant improvement of the earlier obtained limit [1]. Also shown are the limits obtained by AMANDA [2], [3] and Pierre Auger Observatory [22], theoretical bounds obtained by Berezinsky [23], by Waxman and Bahcall [24], by Mannheim et al.(MPR) [20], as well as the atmospheric conventional neutrino fluxes [25].

IV. Conclusion

The neutrino telescope NT200 in Lake Baikal is taking data since April 1998. Due to high water transparency and low light scattering, the detection volume of NT200 for high energy neutrino events is several Megatons and significantly exceeds the instrumented volume. This results in a high sensitivity to diffuse neutrino fluxes from extraterrestrial sources – more than an order of magnitude better than that of underground searches and similar to the published limits of the AMANDA neutrino telescope. The upper limit obtained for a diffuse all-flavor neutrino flux with E^{-2} shape is $E^2\Phi = 2.9 \times 10^{-7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}$.

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