Search for High-Energy Neutrinos in the Baikal Neutrino Experiment

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Received January 12, 2009

Abstract—A new analysis of the data from the NT200 neutrino telescope based on the reconstruction of parameters for high-energy showers generated in neutrino interactions has yielded new upper limits on the diffuse neutrino fluxes predicted by a number of theoretical models. The upper limit on the all-flavor neutrino flux with an energy spectrum E^{-2} is $E^2 \Phi_\nu < 2.9 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

PACS numbers: 95.55.Vj; 95.85.Ry; 98.70.Sa

DOI: 10.1134/S1063773709100016

Key words: *neutrino astrophysics, neutrino telescopes, Baikal experiment.*

INTRODUCTION

A search for high-energy neutrinos of extraterrestrial origin is a priority direction of research on deep-water (or under-ice) neutrino telescopes that record the Cherenkov radiation of muons or high-energy showers produced by the interaction of neutrinos with the medium.

The diffuse high-energy neutrino flux near the Earth has been generated by neutrino emission from the entire set of neutrino sources over the time from distant cosmological epochs to the present day. The

most probable sources of high-energy neutrinos are galactic and cosmological objects—supernova remnants, microquasars, active galactic nuclei, gamma-ray bursts, etc. The standard approach used by a wide range of theoretical models that describe the generation of neutrino fluxes in cosmic ray sources suggests the production of neutrinos mainly during the decay of π mesons produced in pp and $p\gamma$ interactions. In this case, the neutrino flux emitted by a source contains neutrinos of various flavors in a proportion $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0$. Due to the effect of neutrino oscillations, this ratio changes with distance to the source. According to Super-Kamiokande ex-

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perimental data (Fukuda et al. 1998), the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation length for the chosen oscillation parameters $\delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ and $\sin 2\theta = 1$ is $L_{\text{osc}} \sim 1.3 \times 10^{-4} (E_\nu / 1 \text{ PeV}) \text{ pc}$. Thus, the oscillation length is considerably smaller than the characteristic distances to the presumed astrophysical sources of high-energy neutrinos and the ratio between the various flavors of neutrinos in the detected flux becomes $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$. It should be noted that the neutrinos from the decay of supermassive particles associated, in particular, with grand unification theories GUT (the top-down scenario), could account for a certain part of the diffuse flux.

The most significant results from the investigation of the diffuse neutrino flux at energies above 10 TeV have been obtained in experiments on the Baikal NT200 neutrino telescope (Aynutdinov et al. 2006) and in the AMANDA experiment (Achterberg et al. 2007; Ackermann et al. 2008). The technique of searching for high-energy neutrinos in experiments on the NT200 neutrino telescope is based on the recording of Cherenkov radiation from high-energy electromagnetic and hadronic showers generated in a large water volume around the telescope by neutrino interactions. Hadronic showers are produced in the interactions of all flavors of neutrinos with nuclei through the channels of charged (CC) and neutral (NC) currents. In addition, for the CC interaction of electron and τ neutrinos, the electron energy transforms into the energy of an electromagnetic shower, while a significant fraction of the energy of the τ lepton, as a result of its decay, is transferred to a hadronic or electromagnetic shower. Thus, this technique allows the shape of the diffuse neutrino energy spectrum to be investigated.

The NT200 neutrino telescope has been in operation on Lake Baikal since April 1998. The detector is located at a depth of $\sim 1100 \text{ m}$ and consists of seven peripheral strings and one central string of optical modules (OMs). The length of each string is 68 m. The separation between the central and peripheral strings is 21.5 m. The total number of optical modules in the telescope is 192. To suppress the dark current of the photodetectors and the background from the luminescence of the medium, all optical modules of the telescope were grouped into pairs and switched on for coincidence. Each OM pair forms a measuring channel. The time of the first triggered OM of the channel is chosen as the signal time stamp. The amplitude of one of the OMs chosen beforehand based on the calibration of the telescope's measuring systems is used as the channel amplitude. A detailed description of the design and main functional systems of the NT200 telescope is given in several publications of the Baikal collaboration (Aynutdinov et al. 2006;

Belolaptikov et al. 1997; Aynutdinov et al. 2008a, 2008b).

The results of a search for the signal from high-energy neutrinos based on the NT200 data accumulated from April 1998 to February 2003 were published in Aynutdinov et al. (2006). In this paper, we present the results of a new analysis of these data obtained by taking into account the information about the energy, coordinates, direction of development of showers recorded in the telescope.

THE TECHNIQUE OF SELECTING EVENTS FROM HIGH-ENERGY NEUTRINOS IN THE NT200 NEUTRINO TELESCOPE

As has already been noted above, the search for high-energy neutrinos is based on the selection of events from showers generated by neutrino interactions in the sensitive volume of the telescope. The intensity of the Cherenkov radiation from showers is proportional to their energy with a proportionality factor of $\sim 10^8 \text{ phot TeV}^{-1}$. This circumstance, along with the high Baikal water transparency, allows us to search for events from neutrinos with an energy $E_\nu > 10 \text{ TeV}$ in an effective volume that exceeds the geometric volume of the telescope by more than an order of magnitude. The main source of the background in the search for high-energy neutrinos is the flux of atmospheric muons from the decay of π , K mesons and also from other short-lived particles. However, while the contribution from the former is calculated fairly reliably, the contribution from the latter can be estimated only as an upper limit and is not amenable to a reliable theoretical estimation. In other words, taking the atmospheric muons from the decays of π , K mesons as the only source of the background, we can thus define the flux of high-energy neutrinos and/or the flux of muons from the decay of short-lived particles ("direct-generation" muons) as the subject of our studies. This said, below, we will not turn to the question about the possible contribution from "direct-generation" muons in this paper.

In our analysis, we consider events with a large multiplicity of triggered channels N_{hit} as neutrino candidates. To suppress the background events from atmospheric muons, we select only those events from the total set of experimental data for which the temporal response of the telescope corresponds to the passage of the light signal in the facility from the bottom upward. Such events are selected by limiting the admissible values of the parameter t_{min} characterizing each event:

$$t_{\text{min}} = \min(t_i - t_j) > -10 \text{ ns}, \quad i < j, \quad (1)$$

where t_i and t_j are the triggering times of the i th and j th channels on each triggered string (the channel

number is counted from the top downward from the upper channel of the string), $t_{\min}$ is the minimum difference in the triggering time of any pairs of channels on all of the possible strings (the i th channel on the string is located above the j th channel). Condition (1) eliminates a significant fraction of the events from atmospheric muons from above from the subsequent analysis. The suppression factor for the total data set used in our analysis is 2.5×10^{-3} . Only a relatively small fraction of the events from nearly horizontal atmospheric muons that passed under the facility and triggered a high-energy shower satisfy this selection criterion.

As has already been noted above, the most probable sources of high-energy neutrinos are galactic and extragalactic objects in which charged particles, mostly protons and electrons, are accelerated to ultrahigh energies. In the case of Fermi particle acceleration at shock fronts in a source (see, e.g., Blandford and Ostriker 1980), the neutrino energy spectrum should be similar in shape to the proton spectrum $E^{-\gamma}$ with $\gamma = 2-2.3$. For the top-down scenario of neutrino production by the decay of supermassive elementary particles associated with grand unification theories, the neutrino spectral index should be appreciably smaller, $\gamma \approx 1-2$ (Sigl et al. 1997; Dutta et al. 2000a). Thus, for any production scenario of ultrahigh-energy neutrinos of extraterrestrial origin, the expected diffuse neutrino spectrum is considerably flatter than the spectrum of the atmospheric muons generating background events in the telescope. Analysis of the characteristic features in the experimental shower energy distribution attributable to the spectrum of recorded particles (muons and neutrinos) allows events from high-energy neutrinos to be selected against the background of events from atmospheric muons.

Aynutdinov et al. (2006) presented the results of a search for events from high-energy neutrinos in experiments on the NT200 neutrino telescope based on an analysis of the shape of the distribution of events in the number of triggered channels N_{hit} in the telescope. However, the distribution in N_{hit} does not reflect fully the energy distribution of recorded showers, because the multiplicity of triggered channels depends both on the energy and on the position of the shower vertex relative to the telescope. In this paper, we used a different approach in our data analysis based on the selection of events from high-energy showers and the reconstruction of shower coordinates, energy, and direction of development. In comparison with the technique described by Aynutdinov et al. (2006), this technique allows us to reduce significantly the background level from atmospheric muons and to increase the selection efficiency of neutrino events.

RECONSTRUCTION OF SHOWER PARAMETERS

The Cherenkov radiation of high-energy electromagnetic and hadronic showers is produced by the photons emitted by charged particles of the shower (mostly electrons and positrons). The total number of Cherenkov photons N_{ch} is proportional to the shower energy E_{sh} (Wiebusch 1995; Bezrukov and Butkevich 1999; Alvarez-Muniz and Zas 1998). In modeling the signal and background, we used the relation from Wiebusch (1995) for electromagnetic showers,

$$N_{\text{ch}} = 1.04 \times 10^5 E_{\text{sh}} (\text{GeV}), \quad (2)$$

and the relation from Alvarez-Muniz and Zas (1998) for hadronic showers,

$$N_{\text{ch}} = 1.27 \times 10^5 f(\epsilon) E_{\text{sh}} (\text{GeV}), \quad (3)$$

$$\epsilon = \log(E_{\text{sh}}/1 \text{ TeV}),$$

$$f(\epsilon) = -1.27 \times 10^{-2} - 4.76 \times 10^{-2}(\epsilon + 3) - 2.07 \times 10^{-3}(\epsilon + 3)^2 + 0.52\sqrt{\epsilon + 3}.$$

An overwhelming majority of the Cherenkov photons from high-energy showers are emitted from the region of the shower maximum by particles moving along the direction of shower development. As a result, the angular distribution of the Cherenkov radiation of a shower is a highly anisotropic function with a maximum near angles $\vartheta \approx 42^\circ$ relative to the shower axis. This peculiarity of the angular distribution and weak scattering of light in the water of Lake Baikal allow the shower direction to be reconstructed using amplitude information from the optical detectors of the neutrino telescope.

The coordinates, energy, and orientation of showers recorded by the NT200 telescope are reconstructed in two stages. At the first stage, the shower coordinates are reconstructed using temporal information from the telescope's triggered channels (in the approximation of a point shower). The reconstruction procedure consists in determining the shower coordinates that correspond to the minimum of the functional

$$\chi_t^2 = \frac{1}{N_{\text{hit}} - 4} \sum_{i=1}^{N_{\text{hit}}} \frac{(T_i(x, y, z, t_0) - t_i)^2}{\sigma_{ti}^2}, \quad (4)$$

where t_i is the time of the i th triggered channel, T_i is the expected triggering time of the i th channel from a shower with coordinates $r_{\text{sh}}(x, y, z)$, and σ_{ti} is the uncertainty of the time measurement. At the second stage, the shower energy and direction are reconstructed by the maximum likelihood method using the shower coordinates reconstructed at the first stage. As the polar and azimuthal angles that characterize the direction of shower development and the shower

Fig. 1. Relative difference of the shower vertex coordinates before and after applying the reconstruction procedure.

energy, we choose the values of the variables θ , φ , and E_{sh} that correspond to the minimum of the functional

$$L_A = - \sum_{i=1}^{N_{\text{hit}}} \ln p_i(A_i, E_{\text{sh}}, \mathbf{\Omega}_{\text{sh}}(\theta, \varphi)). \quad (5)$$

The functions $p_i(A_i, E_{\text{sh}}, \mathbf{\Omega}_{\text{sh}}(\theta, \varphi))$ describe the probability of recording a signal with amplitude A_i in the i th triggered channel from a shower with energy E_{sh} and axis direction $\mathbf{\Omega}_{\text{sh}}$. These functions were obtained by modeling the response of the telescope's optical module to the Cherenkov radiation of a shower by taking into account the propagation of light in water and the relative orientation of the optical module and shower.

MODELING OF EVENTS FROM ATMOSPHERIC MUONS

We estimated the expected number of background events by calculating the flux of atmospheric muons at the depth of the detector and modeling the telescope's response to these muons. The sea-level flux of muons from the interaction of cosmic rays in the

Earth's atmosphere was calculated with the CORSIKA5.7 code (Heck and Knapp 1998a,b) using the spectrum and chemical composition of primary cosmic rays suggested by Wiebel-Sooth and Biermann (1999). The primary interaction of protons and nuclei in the Earth's atmosphere was modeled using the QGSJET model (Kalmykov and Ostapchenko 1993). The propagation of muons in water to the detector depth was modeled with the MUM code (Bugaev et al. 2001). Subsequently, we modeled the telescope's response to single muons and groups of muons taking into account the electromagnetic secondaries of muons. The total number of modeled events from atmospheric muons is 1.2×10^9 , which corresponds to 3671 days of continuous data collection by the NT200 telescope. At the next stage, we selected events with a large multiplicity of triggered channels ($N_{\text{hit}} > 15$) satisfying the selection condition (1) and reconstructed the shower parameters. To further suppress the background from groups of muons and to improve the reconstruction quality, we used additional event selection criteria: $N_{\text{hit}} > 18$, $\chi_t^2 < 3$, and $L_A < 20$. Figures 1–4 illustrate the efficiency of reconstructing the coordinates, energies,

Fig. 2. Distribution of the logarithm of the ratio of the reconstructed and modeled energies of showers from atmospheric muons.

and directions of development for the high-energy showers expected from atmospheric muons. Figure 1 presents the distribution of events in variable $\delta r/r = |\mathbf{r}_{\text{rec}} - \mathbf{r}|/|\mathbf{r}|$, where $\mathbf{r}$ and $\mathbf{r}_{\text{rec}}$ are the modeled and reconstructed coordinates of the shower vertex relative to the center of the telescope. The coordinate reconstruction accuracy is 7–8%. The distribution of events in logarithm of the ratio of the reconstructed shower energy to the modeled one is shown in Fig. 2. The shower energy reconstruction accuracy on a logarithmic scale is 19–21%. The distribution of events in angle ψ between the modeled and reconstructed directions of showers is presented in Figs. 3 and 4. The median angle of this distribution is 4.5° and the mean angle is 6.2° . The distribution in angle ψ (Fig. 3) has a characteristic feature in the range $50^\circ < \psi < 100^\circ$, which contains (0.2–0.4)% of the total number of events. In our analysis, these events are reconstructed mostly as showers from below the horizon. The nature of this inaccuracy of the reconstruction algorithm consists in the following. As has already been noted above, the Cherenkov radiation of a high-energy shower in water propagates mainly along a cone with an opening half-angle $\vartheta \approx 42^\circ$ relative to the shower axis. Therefore, for a certain class of shower events, the telescope's response is

degenerate with respect to the replacement of the true zenith angle θ of the direction of shower development by an angle of the order of $\theta \pm 2\vartheta$, which leads to an erroneous reconstruction of the shower axis direction. The zenith-angle and energy distributions of events expected from atmospheric muons and satisfying all selection criteria are presented in Figs. 5 and 6 and are discussed below.

MODELING OF NEUTRINO EVENTS

The number of expected events from an isotropic diffuse neutrino flux over the observing time T is described by the expression

$$N_\nu = T \int d\Omega \int dE_{\text{sh}} V_{\text{eff}}(\Omega, E_{\text{sh}}) \quad (6)$$

$$\times \sum_k \int N_A \rho_{\text{H}_2\text{O}} \frac{d\sigma_{\nu k}}{dE_{\text{sh}}} \Phi_\nu(\Omega, E_\nu, X) dE_\nu,$$

$$X(\Omega) = \int_0^L \rho_{\text{earth}}(l) dl, \quad (7)$$

where $\Phi(\Omega, E_\nu, X)$ is the flux of neutrinos with energy E_ν in direction Ω at a point of interaction in

Fig. 3. Distribution of events in angle ψ between the modeled and reconstructed directions of development of showers from atmospheric muons.

water with coordinate X , E_{sh} is the shower energy at the vertex of the neutrino interaction, $X(\Omega)$ is the column density of the medium through which the neutrino passes before the interaction in water, and $V_{\text{eff}}(\Omega, E_{\text{sh}})$ is the effective shower recording volume. The subscript ν characterizes the neutrinos or antineutrinos of different flavors. The subscript k corresponds to the summation over CC- and NC-interactions; N_A is the Avogadro number. The neutrino fluxes satisfy the boundary conditions $\Phi_{\nu_i}(E, 0) = A_{\nu_i} f_{\nu_i}(E)$, where $f_{\nu_i}(E)$ are the diffuse neutrino spectra near the Earth predicted by theoretical models that describe the processes in cosmic ray sources or other sources of diffuse neutrinos, A_{ν_i} is the normalization factor. Here, we assume that the ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ holds near the Earth, the ratio of the neutrino and antineutrino fluxes is $\nu/\bar{\nu} = 1$, and the energy spectra of neutrinos of different flavors are described by a single distribution $f_\nu(E)$.

The solution of equation (6) was obtained by modeling the neutrino passage through the Earth using the neutrino cross sections from Gandhi et al. (1996, 1998) and Lai et al. (1997), the τ -lepton decay cross sections from Dutta et al. (2000b) and Lipari (1993), and the model of the Earth's profile from Gandhi et al. (1996) and Dziewonski and Anderson (1981).

We modeled the telescope's response to the Cherenkov radiation of showers from neutrino interactions in the sensitive volume of the telescope by taking into account the longitudinal shower development, the light absorption and scattering in water, and the dispersion of the speed of light in water. In the case of electromagnetic showers with energy $E_{\text{sh}} > 2 \times 10^7$ GeV and hadronic showers with $E_{\text{sh}} > 10^9$ GeV, the increase in the longitudinal shower size due to the Landau–Pomeranchuk–Migdal effect (Migdal 1956) was taken into account by an additional factor proportional to $E_{\text{sh}}^{1/3}$ (Alvarez-Muniz and Zas 1997).

Fig. 4. Distribution of events in angle ψ between the modeled and reconstructed directions of development of showers for angles $\psi < 20^\circ$.

RESULTS OF OUR ANALYSIS OF THE EXPERIMENTAL DATA

During 1038 days of effective data collection by the NT200 telescope for the period from April 1998 to February 2003, 3.45×10^8 events were recorded based on the selection condition ≥ 4 triggered channels in an event. The procedures for calibrating the telescope's measuring systems and analyzing the experimental data quality were described in detail by Aynutdinov et al. (2006, 2008a). For the subsequent analysis, we selected 18 384 events with $N_{\text{hit}} > 15$ triggered channels in an event and satisfying condition (1). When the number of triggered channels in an event was determined, the channels in which only one of the two optical modules operated and the upward-oriented channels were excluded from our analysis, because the uncertainty in their sensitivity to events under the facility was greater than that for the downward-oriented channels. As was shown by Aynutdinov et al. (2006), the distributions of events from the selected data set in parameters N_{hit} and t_{min}

are in good agreement with the expected distributions from atmospheric muons. At the next stage of our analysis, we applied the reconstruction procedure described above to the experimental events and selected events satisfying the criteria $N_{\text{hit}} > 18$, $\chi_t^2 < 3$, and $L_A < 20$, which were used to select the shower events expected from atmospheric muons.

Figure 5 presents the distribution of experimental events (filled circles) in zenith angle θ ($\theta = 0^\circ$ for the downward vertical direction), along with the corresponding distributions of modeled (histogram) and reconstructed (rectangles) events from atmospheric muons. In the range of zenith angles $40^\circ < \theta < 90^\circ$ (events from above), there is good agreement between the experimental and theoretical distributions. For $\theta < 40^\circ$, the number of both experimental and expected background events after the reconstruction procedure exceeds the number of modeled background events. This excess is attributable to inaccuracy of the reconstruction algorithm. For $\theta > 90^\circ$, we selected eight experimental events, in good

Fig. 5. Distribution of experimental events in zenith angle (filled circles) and distributions of modeled (histogram) and reconstructed (rectangles) events from atmospheric muons. The dashed histogram describes the expected distribution of reconstructed events from atmospheric neutrinos.

agreement with 12 events expected for atmospheric muons from above that are reconstructed as events from below due to inaccuracy of the reconstruction procedure. The dashed histogram for $\theta > 90^\circ$ corresponds to the expected zenith-angle distribution of events from atmospheric neutrinos. The total number of expected events from atmospheric neutrinos is approximately one event. The procedure for modeling events from atmospheric neutrinos was described by Belolaptikov (2007).

Figure 6 presents the energy distribution of experimental events (filled circles), along with the generated (histogram) and reconstructed (rectangles) distributions expected for atmospheric muons at zenith angles $\theta > 40^\circ$. For angles $\theta < 90^\circ$, the experimental distribution covers the energy range $E_{\text{sh}} < 130$ TeV and agrees well with the expected distribution for showers from atmospheric muons. For zenith angles $\theta > 90^\circ$, the experimental events are distributed in the energy range $E_{\text{sh}} < 10$ TeV, in good agreement

with the distribution expected for showers from atmospheric muons due to inaccuracy of the reconstruction procedure. Our analysis of the energy and angular distributions of experimental events with the statistical and systematic uncertainties revealed no statistically significant deviation from the distributions expected for showers from atmospheric muons.

Based on this result and choosing additional neutrino event selection criteria that suppress considerably the background from atmospheric muons, we can obtain an upper limit on the flux of high-energy neutrinos.

UPPER LIMIT ON THE DIFFUSE FLUX OF HIGH-ENERGY NEUTRINOS

As additional criteria for the selection of events from high-energy neutrinos in the range of zenith angles $180^\circ \geq \theta > 40^\circ$, we used the following constraints on the energy of the showers from neutrinos: $E_{\text{sh}} > 130$ TeV for $40^\circ < \theta < 90^\circ$ and $E_{\text{sh}} > 10$ TeV

Fig. 6. Energy distribution of experimental events (filled circles) and distributions of modeled (histogram) and reconstructed (rectangles) events from atmospheric muons for zenith angles $40^\circ < \theta < 90^\circ$. The distributions of events reconstructed as events from below are shown inside the region bounded by the dashed line.

for $\theta > 90^\circ$. In addition, as candidates for events from neutrinos, we also considered events for which these conditions were not met but which satisfied the selection criteria that we used in our previous data analysis (see, e.g., Aynutdinov et al. 2006).

No events satisfying these selection conditions were recorded in the experiment. The uncertainty in the efficiency of recording neutrino events is 30% and is mainly attributable to the uncertainty in the light absorption length in water. The number of expected background events is 2.3 ± 1.2 , given the statistical and systematic uncertainties in the background estimate. The upper limit on the number of events from high-energy neutrinos at a 90% confidence level was obtained using the technique proposed by Conrad et al. (2003), Feldman and Cousins (1998), and Roe and Woodroffe (1999) and is $n_{90\%} = 2.4$.

The number of expected events N_{mod} from a given diffuse neutrino flux predicted by a specific theoretical model can be determined from Eq. (6). The parameter $\eta = n_{90\%}/N_{\text{mod}}$ characterizes the degree of agreement between the experimental measurements and

theoretical predictions. The values of $\eta < 1$ indicate that the theoretical model is inconsistent with the experimental results. The table gives the expected number of events summed over all flavors of neutrinos N_{mod} , the energy range $\Delta E_{90\%}$ in which 90% of the events are expected, the mean energy $\bar{E}_\nu$ of the expected neutrinos, and the factor $\eta = n_{90\%}/N_{\text{mod}}$ for the diffuse neutrino fluxes predicted by several models of astrophysical sources. The neutrino spectrum suggested by Stecker (2005), the S05 model in the table, was obtained within the framework of a model describing the generation of neutrinos in the central regions of quasars.¹ The remaining data presented in

¹The value of $\eta = 2.5$ for the flux of Stecker (2005) is given in several papers of the Baikal collaboration published after 2006. In finding this value, we disregarded the difference in the fluxes presented by Stecker and Salamon (1996) (an erroneous value, as was pointed out by Stecker (2005)) and Stecker et al. (1992). The correct value of the predicted flux is approximately a factor of 4 lower, which corresponds to $\eta = 10$. In this paper, $\eta = 3.4$ was obtained by applying this correction.

The number of expected events N_{mod} , the energy range $\Delta E_{90\%}$ in which 90% of the events are expected, the mean energy $\bar{E}_\nu$ of the expected neutrinos, and the factor $\eta = n_{90\%}/N_{\text{mod}}$ for various models of astrophysical sources

BAIKAL					AMANDA
Model	$N_{\text{mod}}(\nu_e + \nu_\mu + \nu_\tau)$	$\Delta E_{90\%}$	$\bar{E}_\nu$	$n_{90\%}/N_{\text{mod}}$	$n_{90\%}/N_{\text{mod}}$
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	–

the table refer to the models of neutrino generation in jets from active galactic nuclei (AGNs). The P $p\gamma$ (Protheroe 1996) and M $pp + p\gamma$ (Mannheim 1995) models suggest the production of neutrinos by $p\gamma$ and $pp + p\gamma$ interactions, respectively, in blazar jets. The SeSi spectrum is the characteristic expected neutrino spectrum from blazars obtained using a phenomenological approach by Semikoz and Sigl (2003). The MPR distribution is a combination of the highest possible neutrino fluxes from AGN jets in a wide energy range (Mannheim et al. 2000). For comparison, the table also gives the values of η obtained by analyzing the AMANDA experimental data (Achterberg et al. 2007; Ackermann et al. 2008).

As we see from the table, the diffuse neutrino flux predicted by the P $p\gamma$ model (Protheroe 1996) disagrees with our experimental data. Agreement with the experiment can be achieved by a twofold reduction in the normalization factor of this flux. An increase in the sensitivity of the Baikal experiment by a factor of 2–3 is required to test the remaining models considered.

For a power-law energy spectrum $\Phi_{\nu_i} \propto E_{\nu_i}^{-2}$, the upper limit on the diffuse flux of any of the three flavors of neutrinos is

$$\Phi_{\nu_i + \bar{\nu}_i} E^2 < 9.7 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}. \quad (8)$$

The upper limit on the total all-flavor neutrino flux is a factor of 3 higher than the upper limit (8):

$$\Phi_\nu E^2 < 2.9 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}. \quad (9)$$

This upper limit refers to the energy range $20 \text{ TeV} < E_\nu < 2 \times 10^4 \text{ TeV}$ containing 90% of the expected neutrino events.

The limiting fluxes (8) and (9) are approximately a factor of 2.8 lower than those obtained previously (Aynutdinov et al. 2006). This is because the efficiency of the procedure for selecting neutrino events from the total data set increases significantly in this analysis, which allowed us to relax the selection conditions and, accordingly, to increase the effective high-energy neutrino recording volume.

Figure 7 presents the experimental upper limits on the diffuse all-flavor neutrino flux for a power-law spectrum E^{-2} obtained by analyzing data from the Baikal neutrino telescope (this paper) and in the AMANDA (Achterberg et al. 2007; Ackermann et al. 2008) and MACRO (Ambrosio et al. 2002) experiments. In addition, Figure 7 presents the expected fluxes of atmospheric neutrinos from the decay of π , K mesons (Volkova 1980) from nearly horizontal and vertical directions (upper and lower bottom curves) and from the decay of charmed particles (Ryazhskaya et al. 2002; ν_{pr} curves). In Fig. 7, the B, MPR, and WB lines correspond to the theoretical upper limits on the admissible diffuse neutrino flux obtained by Berezhinsky (2005), Mannheim et al. (2000), and Waxman and Bahcall (1999). The TD curve corresponds to the predicted diffuse neutrino fluxes from topological defects (Semikoz and Sigl 2003).

The upper limits on the diffuse neutrino flux for various energy spectra $f(E_\nu)$ (in particular, the limiting fluxes (8) and (9)), along with the limits obtained in the AMANDA experiment (Achterberg et al. 2007; Ackermann et al. 2008), are the most stringent ones among the currently existing experimental upper limits.

Fig. 7. Experimental and theoretical upper limits on the diffuse flux of high-energy neutrinos (for comments, see the text).

ACKNOWLEDGMENTS

This work was supported by the Ministry of Science and Education of the Russian Federation, the Ministry of Science and Education of Germany, the Russian Foundation for Basic Research (project nos. 08-02-00432-a, 08-02-10010-k, 07-02-00791, 08-0200198, and 08-02-10001), and a grant from the President of Russia (NSh-321.2008.2).

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Translated by G. Rudnitskii