Search for high energy neutrinos with the BAIKAL underwater detector NT-96

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Abstract. We present the results of a search for high energy neutrinos with the Baikal underwater Cherenkov detector NT-96. An upper limit to the flux of $\nu_e + \nu_{\mu} + \bar{\nu}_{\mu}$ of $E^2 \Phi(E) < 1.4 \cdot 10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV is obtained, assuming an $E^{-2}$ behavior of the neutrino spectrum.

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1. Introduction

The ultimate goal of large underwater neutrino telescopes is the identification of extraterrestrial neutrinos of high energy. In this paper we present results of a search for neutrinos with $E_\nu > 10$ TeV obtained with the deep underwater neutrino telescope NT-96 at Lake Baikal.

The used search strategy for high energy neutrinos relies on the detection of the Cherenkov light emitted by the electro-magnetic 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 the DUMAND [1] and the AMANDA [2] collaborations to obtain upper limits on the diffuse flux of high energy neutrinos.

We select events with high multiplicity of hit channels corresponding to bright cascades. The volume considered for generation of cascades is essentially below the geometrical volume of NT-96. A cut is applied which accepts only time patterns corresponding to upward traveling light signals (see below). Only the fewer atmospheric muons with large zenith angles may escape detection and illuminate the array exclusively via bright cascades below the detector. These events then have to be rejected by a stringent multiplicity cut.

Neutrinos produce showers and high energy muons through CC-interactions

\[ \nu_l (\bar{\nu}_l) + N \rightarrow l^- (l^+) + \text{hadrons}, \]  

through NC-interactions

\[ \nu_l (\bar{\nu}_l) + N \rightarrow \nu_l (\bar{\nu}_l) + \text{hadrons}, \]  

where $l = e$ or $\mu$, and through resonance production [3, 4, 5]

\[ \bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}, \]  

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

2. Detector

The deep underwater Cherenkov detector NT-96, an intermediate stage of the Baikal Neutrino Telescope NT-200, has been operated since April 1996 till March 1997 [6, 7]. The detector comprises 96 optical modules (OM) at 4 vertical strings. The OMs are grouped in pairs along the strings. They contain 37-cm diameter QUASAR PMTs [8, 9, 10]. The two PMTs of a pair are switched in coincidence in order to suppress light background and PMT noise. A pair defines a channel. A muon-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 such events, amplitude and time of all fired channels are digitized and sent to shore.

3. The data

Within the first 70 days of effective data taking, $8.4 \cdot 10^7$ events with the muon trigger $N_{hit} \geq 4$ have been selected. For this analysis we used events with $\geq 4$ hits along at least one of all hit strings. The time difference between any two channels deployed on the same string was required to obey the condition:

$$| (t_i - t_j) - z_{ij}/c | < a \cdot z_{ij} + 2\delta, \quad (i < j),$$

(4)

with $\delta = 5$ nsec and $a = 1$ nsec/m. The $t_i$, $t_j$ are the arrival times at channels $i, j$, and $z_{ij}$ is their vertical distance. This condition has been used for almost vertically up-going muons selection earlier [6, 7].

8608 events survive the selection criterion (4). Fig.1 shows the hit multiplicity distribution for these events (dashed histogram) as well as the expected one for background showers produced by atmospheric muons (solid histogram). The experimental distribution is consistent with the theoretical expectation within a factor 2. This difference can be explained by the
Figure 2. Effective volumes of NT-96 for isotropic electron and muon neutrinos (solid lines). The dashed lines represent the effective volumes folded with the neutrino absorption probability in the Earth.

uncertainty of the atmospheric muon flux close to horizon at the detector depth [3, and by uncertainties in the dead-time of individual channels. Since no events with $N_{hit} > 24$ are found in our data we can derive upper limits on the flux of high energy neutrinos which produce the events with multiplicity $N_{hit} > 25$.

The energy dependences of the effective volumes for isotropic electron and muon neutrinos are shown in Fig.2 (solid lines). Also shown are the effective volumes folded with the neutrino absorption probability in the Earth (dashed lines).

4. The limits to the diffuse neutrino flux

The shape of the neutrino spectrum was assumed to behave like $E^{-2}$ as typically expected for Fermi acceleration. In this case, 90% of expected events would be produced by neutrinos from the energy range $10^4 \div 10^7$ GeV with the center of gravity around $2 \cdot 10^5$ GeV. Comparing the calculated rates with the upper limit to the actual number of events, 2.3 for 90% CL, and assuming the flavor ratios $\Phi_{\nu_\mu} = \Phi_{\nu_\mu} = \Phi_{\nu_e}$ due to photo-meson

4
Figure 3. Upper limits to the differential flux of high energy neutrinos obtained by different experiments as well as upper bounds for neutrino fluxes from a number of different models. Dot-dash curves labeled WB and GRB(WB) - upper bound and neutrino intensity from GRB estimated by Waxman and Bahcall (1997,1999); dashed curve labeled AGN(M) - neutrino intensity from AGN (Mannheim model A, 1996); solid curves labeled MPR - upper bounds for $\nu_\mu + \bar{\nu}_\mu$ in Mannheim et al. (1998) for pion photo-production neutrino sources with different optical depth $\tau$ (adapted from ref.17). The triangle denotes the limit obtained by the Frejus for an energy of 2.6 TeV : $7 \cdot 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$.

production of $\pi^+$ followed by the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$ for extraterrestrial sources [13, 14], we obtain the following upper limit to the diffuse neutrino flux:

$$\frac{d\Phi_\mu}{dE} E^2 < 1.4 \cdot 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}. \quad (5)$$

New theoretical upper bounds to the intensity of high-energy neutrinos from extraterrestrial sources have been presented recently [13, 14]. These upper bounds as well as our limit and limits obtained by DUMAND [1], AMANDA [2], EAS-TOP [5] and FREJUS [16] experiments are shown in Fig.3. Also, the atmospheric neutrino fluxes [18] from horizontal and vertical directions (upper and lower curves, respectively) are presented.
For resonant process (3) our 90% CL limit is:

\[
\frac{d\Phi_\nu}{dE_\nu} \leq 3.6 \times 10^{-18} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}.
\]  

This limit lies between limits obtained by DUMAND \(1.1 \times 10^{-18}\) cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)GeV\(^{-1}\) and EAS-TOP \(7.6 \times 10^{-18}\) cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)GeV\(^{-1}\).

The new limits (5) and (6) have been obtained with underwater detector NT-96. Analysis of 3 years data taking with NT-200 would allow us to lower this limit by another order of magnitude.

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