THE LAKE BAIKAL EXPERIMENT: SELECTED RESULTS

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ABSTRACT

We review the present status of the Baikal Neutrino Project. The construction and performance of the large deep underwater Cherenkov detector NT-200 with 192 PMTs , which is currently taking data in Lake Baikal, are described. Some results from intermediate detector stages are presented.

1. Detector

The deep underwater Cherenkov detector *NT-200*, the medium-term goal of the BAIKAL collaboration [1,2,3], was put into operation at April 6th, 1998. *NT-200* is deployed in Lake Baikal, Siberia, 3.6 km from shore at a depth of 1.1 km. The detector comprises 192 optical modules (OM) at 8 vertical strings, see Fig.1.

The OMs are grouped in pairs along the strings. They contain 37-cm diameter *QUASAR* PMTs which have been developed specially for our project [1,2,4]. The two PMTs of a pair are switched in coincidence in order to suppress background from bioluminescence and PMT noise. A pair defines a *channel*.

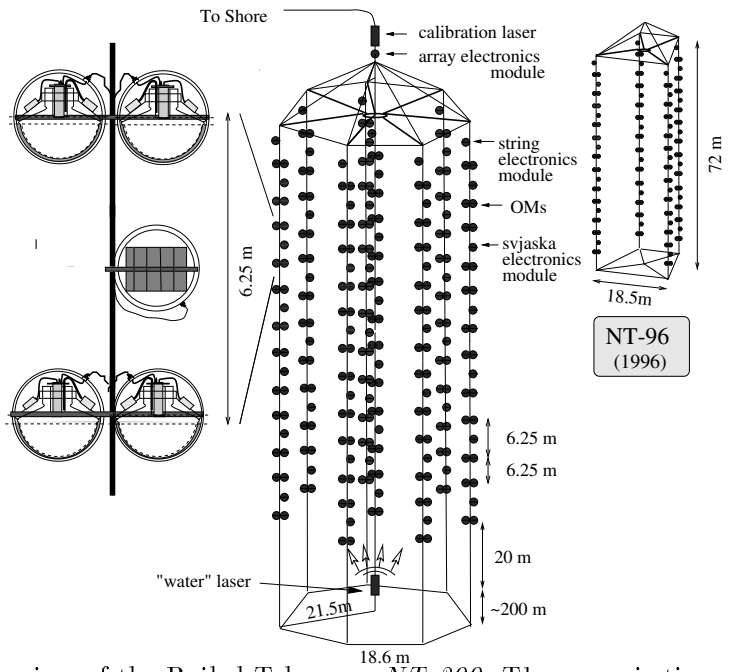

Fig. 1. Schematic view of the Baikal Telescope *NT-200*. The array is time-calibrated by two nitrogen lasers. The one (fiber laser) is mounted just above the array. Its light is guided via optical fibers to each OM pair. The other (water laser) is arranged 20 m below the array. Its light propagates directly through the water. The expansion left-hand shows 2 pairs of optical modules ("svjaska") with the svjaska electronics module, which houses parts of the read-out and control electronics. Top right, the 1996 array *NT-96* is sketched.

All OMs face downward, with the exception of the OMs of the second and eleventh layers, which look upward. The distance between downward oriented layers is 6.25 m, the distance between layers facing to each other (layers 1/2 and 10/11) is 7.5 m, the distance between back-to-back layers (2/3 and 11/12) is 5.0 m.

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. A separate *monopole trigger* system searches for clusters of sequential hits in individual channels which are characteristic for the passage of slowly moving, bright objects like GUT monopoles.

In April 1993, the first part of *NT-200*, the detector *NT-36* with 36 OMs at 3 strings, was put into operation and took data up to March 1995. A 72-OM array, *NT-72*, run in 1995-96. In 1996 it was replaced by the four-string array *NT-96*. *NT-144*, a six-string array with 144 OMs, was taking data in 1997-98.

Analysis of experimental data taken with intermediate arrays, especially with *NT-36* and *NT-96*, proves the capability of the Baikal neutrino telescope to investigate various problems of neutrino and muon physics. Below we present results which illustrate the capability of the Baikal experiment to search for atmospheric muons and neutrinos, neutrinos induced by neutralino annihilation in the center of the Earth,

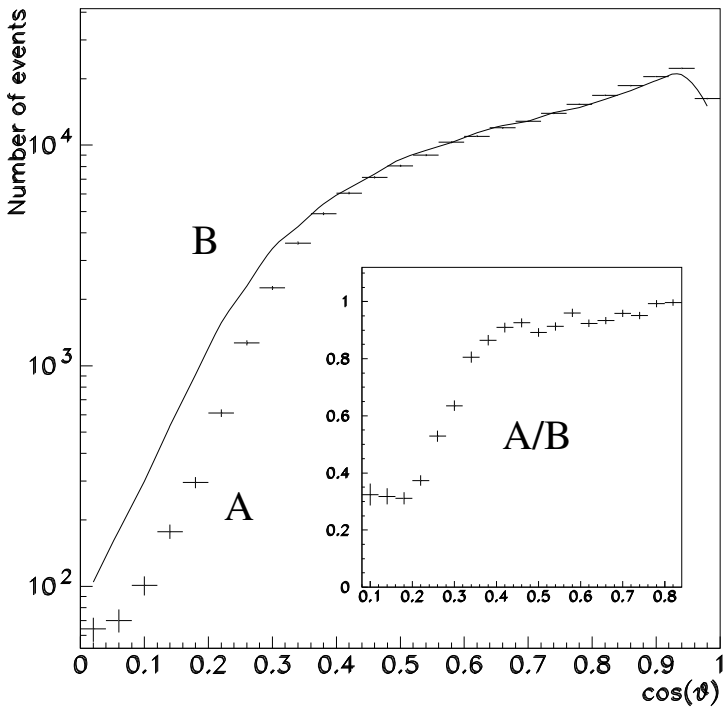

Fig. 2. Atmospheric muons (vs zenith angle θ) as it is measured in the direction to the nearest point of the shore(A) and in opposite one(B) - "open" water. The small picture shows the ratio A to B.

magnetic monopoles and showers produced by high energy neutrinos.

2. Atmospheric Muons

Muon angular distributions as well as depth dependence of the vertical flux obtained from data taken with *NT-36* have been presented earlier [2].

Another example which confirms the efficiency of track reconstruction procedure relates to the investigation of the shore "shadow" in muons with *NT-96*. The Baikal Neutrino Telescope is placed at a distance of 3.6 km to the nearby shore of the lake. The opposite shore is about 30 km away. This asymmetry opens the possibility to investigate the influence of the close shore to the azimuth distribution under large zenith angles, where reconstruction for the comparatively "thin" *NT-96* is most critical. A sharp decrease of the muon intensity at zenith angles of 70^0-90^0 is expected. The comparison of the experimental muon angular distribution with MC calculations gives us an estimation of the accuracy of the reconstruction error close to the horizontal direction. Indeed, the *NT-96* data show a pronounced dip of the muon flux in the direction of the shore and for zenith angles larger than 70^0 – in very good agreement with calculations which take into the effect of the shore.

3. Atmospheric Neutrinos

The main results have been obtained with the first small detector *NT-36* - investigation of atmospheric muon flux, searching for nearly vertically upward moving muons and searching for slowly moving GUT monopoles have been presented elsewhere [2,5,6]. Below we present selected results obtained with *NT-96*.

3.1. Identification of nearly vertically upward moving muons

Different to the standard analysis [2], 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 [5,7]. 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.

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 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.3.

Regarding the four detected events as being due to atmospheric neutrinos, one can derive an the upper limit on the flux of muons from the center of the Earth due to annihilation of neutralinos - the favored candidate for cold dark matter.

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 $\rightarrow$	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

The limits on the excess muon flux obtained with underground experiments [8,9,10] 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 $\approx$ 70 days.

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

	Flux limit $(10^{-14} \cdot (cm^2\ sec)^{-1})$			
Zenith angles	*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

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.

3.2. Selection of neutrino events over a large solid angle

The signature of neutrino induced events is a muon crossing the detector from below. With the flux of downward muons exceeding that of upward muons from atmospheric neutrino interactions by about 6 orders of magnitude, a careful reconstruction is of prime importance.

In contrast to first stages of the detector (*NT-36* [5]), *NT-96* can be considered as a real neutrino telescope for a wide region in zenith angle θ. After the reconstruction of all events with ≥ 9 hits at ≥ 3 strings (trigger*9/3*), quality cuts have been applied in order to reject fake events. Furthermore, in order to guarantee a minimum lever arm for track fitting, events with a projection of the most distant channels on the track (Z_{dist}) less than 35 meters have been rejected. Due to the small transversal dimensions of *NT-96*, this cut excludes zenith angles close to the horizon.

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.

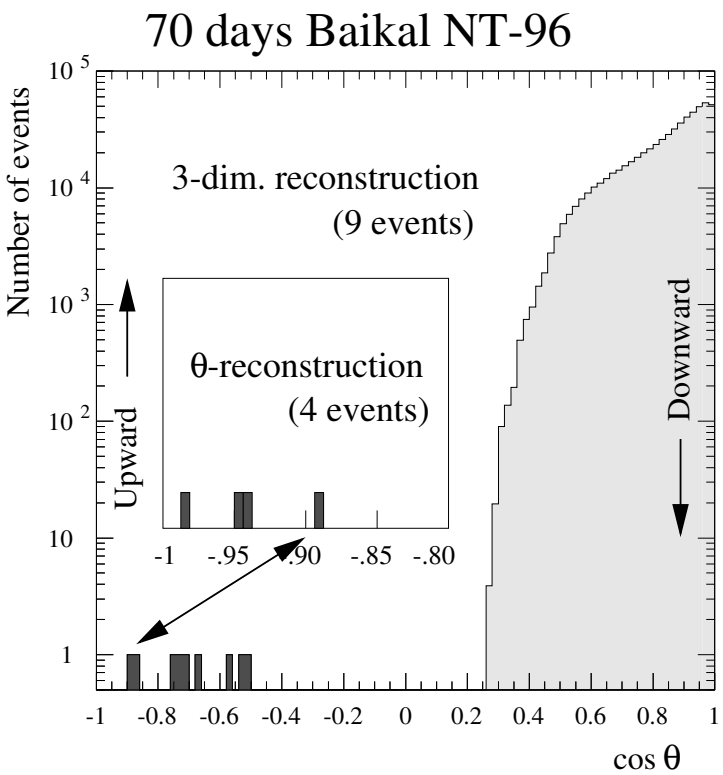

Fig. 3. Experimental angular distribution of events satisfying trigger *9/3*, all final quality cuts and the limit on Z_{dist} (see text). The sub-picture shows the events selected by using the method described in subsection 3.1. The event found by both algorithms is marked by the arrow.

The reconstructed angular distribution of $2 \cdot 10^7$ events taken with *NT-96* in April/September 1996 – after all cuts – is shown in Fig.3.

From 70 days of *NT-96* data, 12 neutrino candidates have been found. Nine of them have been fully reconstructed. Three nearly upward vertical tracks (see subsection 3.1) hit only 2 strings and give a clear zenith angle but ambiguities in the azimuth angle – similar to the two events from *NT-36* [2)]. This is in good agreement with MC expectations.

4. Search for Fast Monopoles ($\beta > 0.75$)

Fast bare monopoles with unit magnetic Dirac charge and velocities greater than the Cherenkov threshold in water ($\beta = v/c > 0.75$) are promising survey objects for underwater neutrino telescopes. For a given velocity β the monopole Cherenkov radiation exceeds that of a relativistic muon by a factor $(gn/e)^2 = 8.3 \cdot 10^3$ ($n = 1.33$ - index of refraction for water) [11,12)]. Therefore fast monopoles with $\beta \geq 0.8$ can be detected up to distances 55 m $\div$ 85 m which corresponds to effective areas of $(1\text{–}3) \cdot 10^4$ m^2.

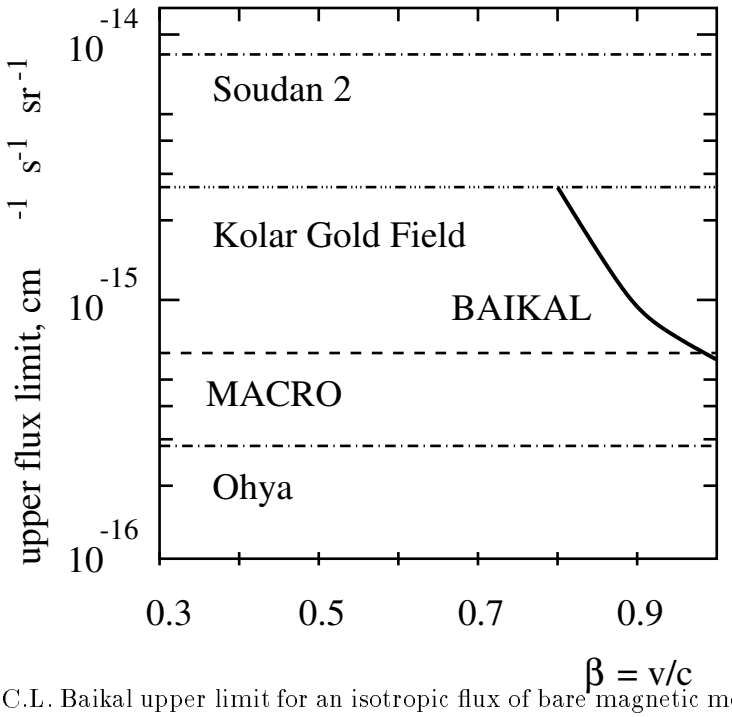

Fig. 4. The 90% C.L. Baikal upper limit for an isotropic flux of bare magnetic monopoles compared with other published limits.

The natural way for fast monopole detection is based on the selection of events with high multiplicity of hits. In order to reduce the background from downward atmospheric muons we restrict ourself to monopoles coming from the lower hemisphere.

Two independent approaches have been used for selection of upward monopole candidates from the 70 days of *NT-96* data. The first one is similar to the method which was applied to upward moving muons (see subsection 3.1), with an additional cut $N_{hit} > 25$ on the hit multiplicity. The second one cuts on the value of space-time correlation, followed by a cut $N_{hit} > 35$ on the hit multiplicity. The upper limits on the monopole flux obtained with the two different methods coincide within errors.

The same type of analysis was applied to the data taken during 0.42 years lifetime with the neutrino telescope *NT-36* [13].

The combined 90% C.L. upper limit obtained by the Baikal experiment for an isotropic flux of bare fast magnetic monopoles is shown in Fig.4, together with the best limits from underground experiments Soudan2, KGF, MACRO and Ohya [14,15,16,17] in Fig.4.

5. Search for Very High Energy Electron Neutrinos

In this section we present very preliminary results with the aim to illustrate the capability of the Baikal Neutrino Telescope to search for extraterrestrial high energy neutrinos from AGNs, GRBs and other sources.

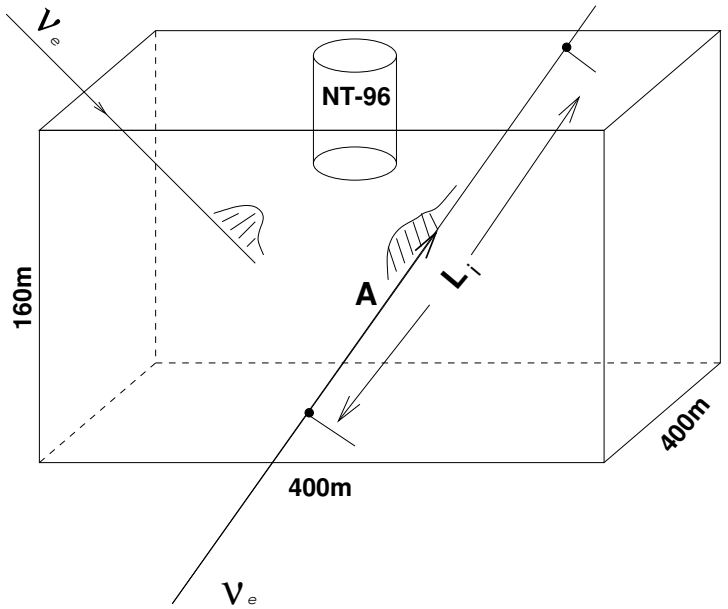

Fig. 5. The scheme illustrating the idea of neutrino induced cascades detection in *NT-96*.

The idea used here to search for high energy electron neutrinos ($E_\nu > 100$ TeV) is to detect the Cherenkov light emitted by the electromagnetic and (or) hadronic particle cascade produced at the neutrino interaction vertex in the sensitive volume of the neutrino telescope. Earlier this idea has been used by DUMAND [18] and AMANDA [19] to obtain upper limits on the diffuse flux of high energy neutrinos.

In order to reduce the background from downward moving atmospheric muons we restrict ourself to cascades produced in a sensitive volume below the detector (see Fig.5) and cause high multiplicity events in detector. The trigger conditions for event selection are the same as those which were used for fast monopole detection (see sec.4).

The effective volumes of *NT-96* averaged over neutrino directions for detection of cascades with energy E_{sh} are presented in Fig.6. The curves marked as "DOWN", "UP" and "TOTAL" correspond to effective volumes averaged over lower and upper hemisphere and over all directions. Also effective volumes of detectors SPS (DUMAND) and AMANDA-A are presented in Fig.6.

After analysis of 70 days of *NT-96* data no evidence for any neutrino-induced cascades is found.

5.1. The limit to the $\tilde{\nu}_e$ flux at the W resonance energy

Although the neutrino-electron interactions can generally be neglected with respect to neutrino-nucleon interactions due to the small electron mass, the resonance cross section of $\tilde{\nu}_e e$ interaction at 6.3 PeV is larger than the νN cross section at any energy up to 10^{21} eV.

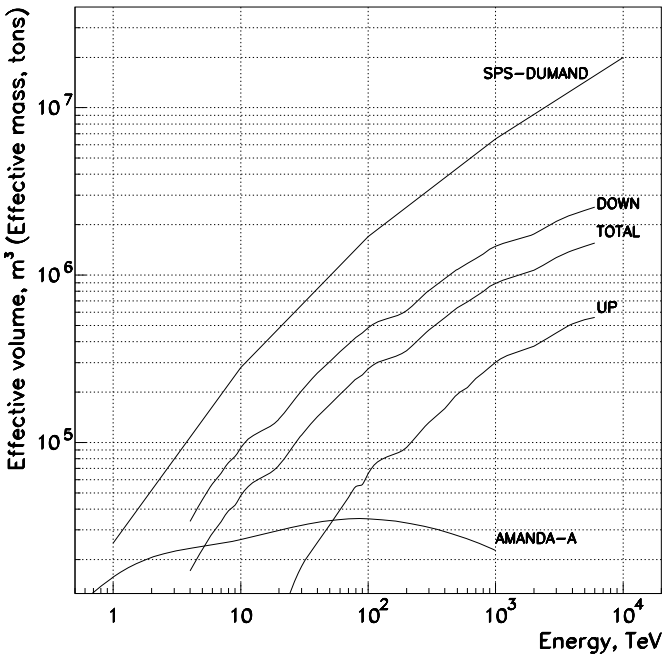

Fig. 6. Effective volumes of *NT-96*, SPS and AMANDA-A. "DOWN", "UP" and "TOTAL" correspond to effective volumes of *NT-96* averaged over lower and upper hemisphere and over all directions of neutrino velocity, respectively.

The resonant cross section at 6.3 PeV for $\tilde{\nu_e}e$ scattering with a hadronic cascade in the final state:

$$\tilde{\nu_e} + e \rightarrow W^- \rightarrow hadrons \tag{1}$$

is $3.41 \times 10^{-31}\mathrm{cm}^2$ [20]. The cross section averaged over the energy range

$$\Delta E = (M_w + 2\Gamma_w)^2/2m_e - (M_w - 2\Gamma_w)^2/2m_e, \tag{2}$$

$$M_w = 80.22GeV, \;\; \Gamma_w = 2.08GeV$$

is $\bar{\sigma} = 1.12 \times 10^{-31}\mathrm{cm}^2$. Eq.3 is used to calculate the upper limit on the diffuse flux of $\tilde{\nu_e}$:

$$\frac{dF_{\tilde{\nu}}}{dE_{\tilde{\nu}}} \leq \frac{2.3}{\frac{10}{18}\rho N_A \bar{\sigma} T \Omega_{eff} V_{eff} \Delta E}. \tag{3}$$

Here T is the detector livetime (70 days), Ω_{eff} and V_{eff} are the average effective solid angle and volume of the detector respectively.

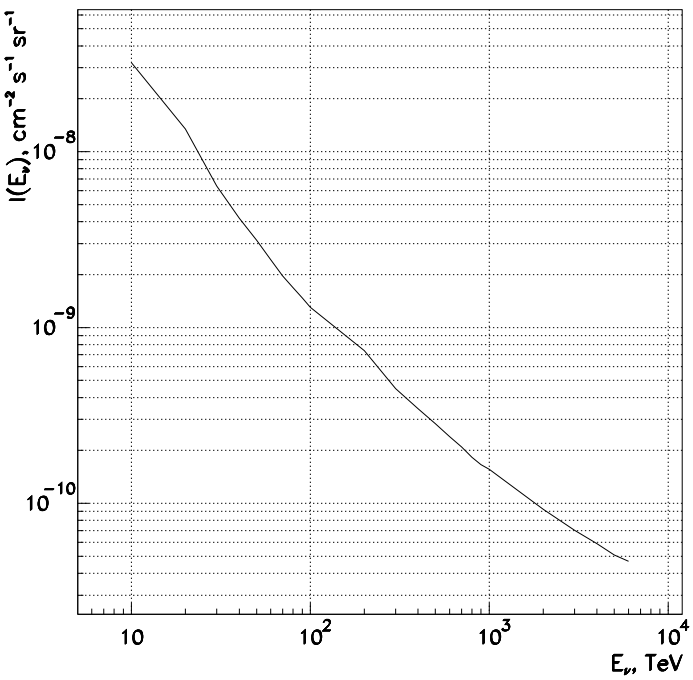

Fig. 7. The 90% C.L. Baikal upper limit on the integral diffuse flux of high energy $\nu_e + \tilde{\nu_e}$ neutrinos under the assumption of a $\delta(E_\nu - E)$ behavior of the neutrino flux.

The 90% CL limit at the W resonance energy is:

$$\frac{dF_{\tilde{\nu}}}{dE_{\tilde{\nu}}} \leq 3.7 \times 10^{-18} cm^{-2} s^{-1} sr^{-1} GeV^{-1}. \quad (4)$$

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

5.2. The limit to the $\nu_e + \tilde{\nu_e}$ flux

For setting a limit to the $\nu_e + \tilde{\nu_e}$ flux we have used the cross sections for $\nu_e(\tilde{\nu_e})$ CC-interactions with nucleons [20)]

$$\nu_e(\tilde{\nu_e}) + N \stackrel{CC}{\rightarrow} e^-(e^+) + hadrons \quad (5)$$

when all neutrino energy is transferred to the cascade. The energy dependence of neutrino absorption in the Earth has been taken into account.

Assuming the $F(E_\nu)dE = A\delta(E_\nu - E)dE$ behavior of the differential neutrino flux the 90% CL limit has been obtained within the $10^{13} \div 6 \times 10^{15}$eV, see Fig.7.

To compare *NT-96* limit with those obtained by SPS and EAS-TOP [21)] we assume that a possible signal of 2.3 events originate in the energy interval from 10^5 to 10^6 GeV with an E^{-2} differential spectrum of neutrinos.

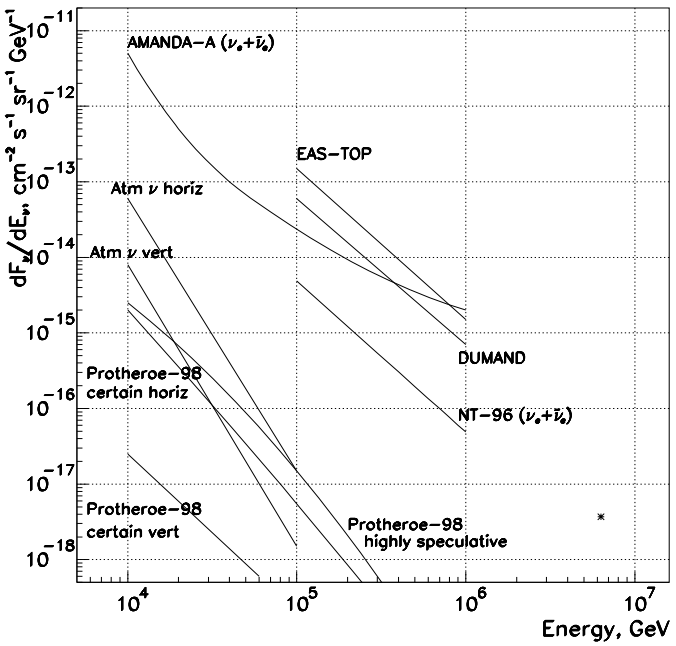

Fig. 8. The upper limits on the differential flux of high energy neutrinos obtained by different experiments and the resulting neutrino fluxes, from a number of different models. Asterisk - the model-independed upper limit (4) on the $\tilde{\nu}_e$ flux obtained at the W resonance energy with *NT-96*.

This limit as well as limits obtained by other groups are shown in Fig.8. Also, the resulting neutrino fluxes from a number of different models [22] as well as backgrounds from atmospheric neutrinos [23] are shown in Fig.8.

6. Conclusions and Outlook

The results obtained with intermediate detector stages show the capability of Baikal Neutrino Telescope to search for the wide variety of phenomena in neutrino astrophysics, cosmic ray physics and particle physics.

The first atmospheric neutrinos have been identified. Also muon spectra have been measured, and limits on the fluxes of magnetic monopoles as well as of neutrinos from WIMP annihilation in the center of the Earth have been derived.

In the following years, *NT-200* will be operated as a neutrino telescope with an effective area between 1000 and 5000 m^2, depending on the energy and will investigate atmospheric neutrino spectra above 10 GeV.

NT-200 can be used to search for neutrinos from WIMP annihilation and for magnetic monopoles. It will also be a unique environmental laboratory to study water processes in Lake Baikal.

Apart from its own goals, *NT-200* is regarded to be a prototype for the development a telescope of next generation with an effective area of 50,000 to 100,000 m^2.

The basic design of such a detector is under discussion at present.

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