Baikal Neutrino Experiment: from NT200 to NT1000

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OUTLINE

Introduction

Neutrino telescope NT200+

Design and Selected Physics Results

Future Gigaton-Volume (GVD) detector NT1000

Preliminary Design
Prototype string for BAIKAL-GVD detector (2008-2009)

Summary
**Baikal - Milestones**

**Since 1980**  Site tests and early R&D started

**1990**  Technical Design Report NT200

**1993**  NT36 started:  the first underwater array  
           the first neutrino events.

**1998**  NT200 commissioned:  start full physics program.

**2005**  NT200+ commissioned (NT200 & 3 outer strings).

**2006**  Start R&D for Gigaton Volume Detector (GVD) – NT1000.

**2008**  In-situ test NT1000 electronics:  6 new technology optical modules

**2009**  Prototype string for NT1000:  12 optical modules

**2011**  GVD cluster (3 strings),  Technical Design Report
NT200: 8 strings (192 optical modules)
Height $\times \varnothing = 70\,\text{m} \times 40\,\text{m}$, $V_{\text{inst}} = 10^5\,\text{m}^3$
Effective area: $1\,\text{TeV} \sim 2000\,\text{m}^2$
Eff. shower volume: $10\,\text{TeV} \sim 0.2\,\text{Mton}$

$\Rightarrow$ ~4 times better sensitivity
$\Rightarrow$ Improve cascade reconstruction

NT200+ = NT200 + 3 outer strings (36 optical modules)
Height $\times \varnothing = 210\,\text{m} \times 200\,\text{m}$, $V_{\text{inst}} = 4 \times 10^6\,\text{m}^3$
Eff. shower volume: $10^4\,\text{TeV} \sim 10\,\text{Mton}$

Quasar photodetector ($\varnothing = 37\,\text{cm}$)

~3.6 km to shore, 1070 m depth

Status of NT200+
NT200+ is operating now in Baikal lake
BAIKAL Water Optical Properties

Absorption length: $22 \pm 2$ m

Scattering length: 30-50 m

$\langle \cos \theta \rangle$: 0.85-0.90

No high luminosity bursts from biology
Ice as a natural deployment platform

Deployment with winches

Shore cable mounting
Selected Physics Results

- Atmospheric muon background
- Atmospheric neutrinos
- WIMP from the Earth Center
- NT200
- Magnetic Monopoles
- WIMP from the Sun
- Neutrinos from GRB
- Diffuse neutrino flux
Low energy muon neutrinos

Lake Baikal (NT200) & South Pole (Amanda)
Complete sky coverage including central parts of Galaxy

Skyplot of NT200 neutrino events
(galactic coordinates)
$E_{\text{thr}}$ 15-20 GeV
385 events from Monte-Carlo
(atmospheric neutrino)
High energy neutrino: searching for diffuse neutrinos based on cascades reconstruction

New analysis of existing data with vertex, energy and direction reconstruction of cascades: improvement of published limit by a factor of ~3

The 90% C.L. “all flavour” limit, $\nu_e: \nu_\mu: \nu_\tau = 1 : 1 : 1$
Cut $E > 10$ TeV for up-going cascades
Cut $E > 100$ TeV for down-going cascades

$E^2 \Phi_n < 2.9 \cdot 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (Cascades Baikal, 2008)

$E^2 \Phi_n < 2.2 \cdot 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (Muons AMANDA-II)

Cascade reconstruction:
$\text{d} \lg E \sim 10\%$;
$\text{d} r \sim (5-10)\%$;
$\text{d} \Psi \sim 5^\circ$

Energy distribution of experimental (red), generated (blue) and reconstructed (black) events from atmospheric muons.
WIMP Neutrinos from the Sun

- Neutralino (WIMP) as favored Dark Matter candidate
- Gravitationally trapped in the Sun (or Earth)
- the Sun would be a neutrino-source (annihilation) \(\rightarrow\) “Indirect“ WIMP searches

Sun-mismatch angle \(\Psi\) (Muon/Sun): data and background (histogram)

No excess of events above atm. \(\nu\) BG \(\rightarrow\) Flux Limits
Search for fast monopoles

For a Dirac charge $g = 68.5$ e, Cerenkov radiation emitted by monopoles is 8300 times more that of a muon.

Event selection criteria:
1. Hit channel multiplicity:
   - $>30$ pairs of PMTs hit.
2. Upward moving light patterns:
   - time-vertical-coordinate correlation.

Background - atmospheric muons.
No excess over the expected background was found.

Limit on a flux of relativistic magnetic monopoles (1003 days of live time):
$$ F < 4.6 \times 10^{-17} \text{ cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} $$

90% C.L. upper limit on the flux of fast monopole
Search for neutrinos from Gamma-Ray Bursts with NT200

Analysis of time and directional correlations between NT200 events and GRB

Experimental data
NT200 data from April 1998 to May 2000
GRB data:
- basic BATSE 4B catalog (triggered bursts): 155
- non-triggered GRB: 148

Signal search:
Time window: \((t_{\text{GRB}} + T_{90} + 5s) - (t_{\text{GRB}}-5s)\)
Half angle of observation cone: \(\Psi = 5^\circ\)

Background:
Time interval \((t_{\text{GRB}} + 1000s) - (t_{\text{GRB}}-1000s)\)
(excluding signal window); \(\Psi = 10^\circ\).

<table>
<thead>
<tr>
<th>GRB</th>
<th>Signal</th>
<th>Backgr.</th>
<th>(\mu_{90})</th>
<th>(N_{90})</th>
</tr>
</thead>
<tbody>
<tr>
<td>All GRB</td>
<td>1</td>
<td>2.7</td>
<td>2.1</td>
<td>1.0\times10^{-2}</td>
</tr>
<tr>
<td>Ttrig. GRB</td>
<td>1</td>
<td>1.6</td>
<td>2.8</td>
<td>2.3\times10^{-2}</td>
</tr>
</tbody>
</table>

\(\mu_{90}\) - event upper limit
\(N_{90}\) - 90% C.L. upper limit on the number of events per GRB

For Waxman – Bahcall spectrum and triggered GRB
\[ E_\nu^2 \Phi_\nu \leq 1.1\times10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \text{ for } E_\nu>100 \text{ TeV}. \]
Gigaton Volume Detector in Lake Baikal – NT1000
Preliminary design

**Layout:**
2304 Optical Modules (OM) at 96 String
String: 24 OM → 2 Sections with 12 OM
Strings are combined in Clusters → 8 strings

**Cascades** (E>100 TeV): $V_{\text{eff}} \sim 0.3–0.8 \text{ km}^3$
$\delta(\lg E) \sim 0.1$, $\delta\theta_{\text{med}} \sim 2^\circ-4^\circ$

**Muons** (E>10 TeV): $S_{\text{eff}} \sim 0.2 – 0.5 \text{ km}^2$
$\delta\theta_{\text{med}} \sim 0.5^\circ-1^\circ$

300 m

NT1000: top view

Cluster of strings

L ~ 345 m

R ~ 60 m

Z ~ 15 m
Optimisation of NT1000 configuration

Basic parameters for optimization:
- \( Z \) – vertical distance between OM
- \( R \) – distance between string and cluster centre
- \( H \) – distance between cluster centres

Trigger: coincidences of neighbouring OM on string

(threshold ~0.5\&3 p.e.)

The compromise between cascade detection volume and muon effective area:
- \( H = 300 \text{ m} \)
- \( R = 60 \text{ m} \)
- \( Z = 15 \text{ m} \)
**The new generation Baikal Optical module**

PM: XP1807(12’’), R8055(13’’), R7081HQE(10’’)

QE ~0.24, QE ~0.2, QE~0.3

HV unit: SHV12-2.0K 1000N, TracoPower

OM controller: PM pulse counter; HV control and monitor; 2 calibration LEDs; RS-485

Amplifier: 2-channels (for monitor), Kamp~10

**Measuring channels**

- PMT 1
- Amplifier
- 90 m coax. cable
- FADC 1
- ...
- PMT 12
- Amplifier
- 90 m coax. cable
- FADC 12

**BEG (FADC Unit):**

- 3 FADC-board: 4-channel, 12 bit, 200 MHz;
- OM power controller: OM power on/off;
- VME controller: trigger logic, data readout from FADC-boards and connection via local bus.
Section of OM – basic cell of NT1000

Section consists of:
12 Optical Modules
1 BEG with 12 FADC channels
1 Service Module (SM) with LED, OM power supply, and acoustic coordinate system.

Trigger: coincidences of neighbouring OM (threch. ~0.5&3 p.e.)
count rate ~ 100 Hz

Data Communication - DSL-modem: dataflow ~0.5Mbit/s
(only time intervals containing PMT pulses are transmitted)
Cluster of strings

**Cluster:** 8 strings × 24 OM

**Cluster DAQ Centre:**
- PC module with optical Ethernet communication to shore;
- Trigger module with 8 FADC channel for the measure of string trigger time;
- DSL-modems for communication with all strings
- Power control system.
In-situ tests of new measuring system with prototype string

The basic goals: investigation and in-situ test of basic elements of the future detector – new optical modules, DAQ system, cabling system, triggering approaches.

NT1000 R&D

NT200+ array is a first step toward NT1000

NT200+ has approximately same scale as a cluster of NT1000 and has allowed to verify detector response simulation, communication and synchronization systems.

• NT1000 optimization on the basis of simulation program tested with NT200+;
• New communication system on the basis of underwater Ethernet and DSL-modems was development and studied with NT200+.
• String time synchronization with laser light source was tested with NT200+.
NT200+ allows to test the time synchronization between the channels of different strings.

Laser intensity: cascade energy \((10^{12} - 5 \times 10^{13})\) \(\gamma\): (10 – 500) PeV

- Laser is visible >200m with high Ampl

Precision of time synchronization 3…4 ns up to distances ~150 m

Deviation of time differences between two NT200+ channels measured with laser from expected value in dependence on distances between channels.
NT1000 prototype string

April 2009: Start of prototype string operation as a part of NT200+
2 Sections with 6 OM, two BEGs with FADC, PC Module, Service Module

String communication center

Optical module
Basic parameters of experimental string - 2009

String length: 110 m
Number of Optical Modules: 12
Number of OM Sections: 2 (6 OM, 6 FADC channels)
Number of FADC channels: 12
Type of PMT: Photonis XP1807 (12”) : 6
Hamamatsu R8055 (13”) : 6
FADC Time Window: 5 mks
FADC frequency: 200 MHz
LED - Optical Fiber calibration system: 1

Data analysis in progress now
1. Monitoring of the optical module operation.
2. Test of the string with LED and LASER.

Experimental data: April – Jun 2009
Monitoring of Optical Module operation

OM monitoring parameters:
- PMT voltage
- PMT count rate
- Temperature
- OM voltages: 12 V, 5 V, -5 V

Examples of PMT count rate monitoring:
- Two month exposition 2009
- Selected time interval ~ 1 day
- PMT voltage and OM temperature during this period for all OM of the string
Time resolution of measuring channels

LED flasher produces pairs of delayed pulses. Light pulses are transmitted to each optical module (channel) via individual optical fibers. Delay values are calculated from the FADC data for all channels.

\[ dT(\text{Expected}) = 497.5 \text{ ns} \]
\[ dT(\text{Experiment}) = 498.3 \text{ ns} \]
\[ \sigma(dT) = 1.6 \text{ ns} \]

Example of a two-pulse LED flasher event (channel #5)
String time resolution

\[ \sigma_{T_{\text{STRING}}} \rightarrow \sigma_{T_{\text{CHANNEL}}} \& \sigma_{T_{\text{SHIFT}}} \]

\[ \sigma_{T_{\text{SHIFT}}} \] - accuracy of compensation of channel delay differences measured with LED flasher:

\[ T_{\text{SHIFT}} \rightarrow \text{DelayPMT(HV) + DelayCable + DelayADC} \]

Test of \( \sigma_{T_{\text{STRING}}} \) with LASER

\[ dT = dT_{\text{LASER}} - dT_{\text{GEOM}} \]

\[ dT_{\text{GEOM}} = (r_2 - r_1) \times c_{\text{water}} \]

dT averaged on all channel combinations with fixed R

\( \sigma_{T_{\text{STRING}}} \sim 2 \text{ ns} \)
CONCLUSION

1. BAIKAL lake experiment is successfully running since 1993
   - The First Underwater Array
   - First Neutrino Candidates

2. NEW configuration NT200+ starts work at April 2005
   - Improved cascade reconstruction, increased effective volume for cascades;
   - NT200+ gives good possibilities to optimise the design and to investigate the key elements of future NT1000 detector.

3. Start R&D for Gigaton Volume (km3-scale) Detector NT1000
   - A “new technology” prototype string was installed: 12 OMs with 12”/13” PMT
   - Preliminary in-situ tests of the prototype string with underwater laser and LED flasher shows good performance of all string elements.
   - NT1000 Technical Design Report is expected at 2011
THANK YOU