neutrinos is equal to 3.7% in each zone and ±2.6% for the entire target.

Thus, the expected total number of ^{71}Ge atoms accumulated over ten exposures in such experiments will be ~ 840 (±4.5%) in each zone, and ~ 1680 (±3.7%) on the entire target (the statistical and systematic uncertainties are combined quadratically).

9. Conclusion

The capture rate of solar neutrinos on a Ga target obtained in SAGE is (65.4 ± 3.8) SNU. The weighted average capture rate of neutrinos on Ga in three gallium experiments (SAGE, GALLEX, and GNO) is (66.1 ± 3.1) SNU, where the statistical and systematic uncertainties are combined quadratically.

By using the results of other solar neutrino experiments and the theory of large-mixing-angle (LMA) neutrino oscillations, we obtained in SAGE for the first time the value of pp-neutrino flux reaching $(3.40 \pm 0.46) \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for neutrinos with the electron flavor arriving on Earth, and the value of total pp-neutrino flux amounting to $(6.0 \pm 0.8) \times 10^{10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

The gallium solar neutrino experiments have shown for the first time that most of the solar neutrinos arriving on Earth are low-energy neutrinos created in the proton–proton reaction and directly confirmed the correctness of the SSM and the LMA solution for solar neutrino oscillations.

To elucidate the reasons for the unexpectedly low neutrino capture rate on Ga in experiments with artificial sources, we developed the concept of a new experiment with a high-intensity neutrino source and the optimized geometry of a Ga target [34].

Up to now, SAGE remains to be the sole experiment in which the pp-neutrino flux has been measured. We plan to pursue the monitoring of solar neutrino fluxes and to make preparations for a new experiment with a high-intensity neutrino source and the optimized geometry of a Ga target.

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BAIKAL neutrino experiment

G V Domogatsky

1. Introduction

The Baikal neutrino experiment is rooted in 1959–1960, when M A Markov [1] proposed the idea of large-scale underground and deep-sea experiments for studying the properties of neutrinos and the natural sources of their origin. The idea proved to be extremely fruitful. Investigations performed under conditions of the drastically reduced background of penetrating cosmic radiation, when huge volumes of the surrounding soil or water themselves serve as targets for high-energy neutrinos, made it possible to achieve a fundamentally new sensitivity level of experiments, allowing the study of rare processes which cannot be virtually detected in ground-based laboratories. The underground investigations

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Table 1. Cherenkov high-energy neutrino detectors in natural media (water and Antarctic ice). The effective masses of detectors are presented for 100-TeV events.

Detector*	Optical modules	Effective mass, Mt	Depth, m	Construction years	State
'Baikal'	230	10	1100 – 1300	1993 – 1998	Operating
AMANDA	677	15	1350 – 1850	1994 – 2000	Closed (2009)
ANTARES	900	10	2050 – 2400	2002 – 2008	Operating
IceCube	900	10	1350 – 2250	2005 – 2011	Operating
KM3NeT (NEMO)	≈ 10000	≈ 1000	2300 – 3300	≈ 2017	Being developed
KM3NeT (NESTOR)	≈ 10000	≈ 1000	2000 – 4000		
KM3NeT (ANTARES)	≈ 10000	≈ 1000	1400 – 2400		
'Baikal NT-1000'	≈ 2500	600 – 800	800 – 1300	≈ 2018	Being developed

* AMANDA — Antarctic Muon And Neutrino Detector Array, ANTARES — Astronomy with a Neutrino Telescope and Abyss environmental RESearch, KM3NeT — KM3 Neutrino Telescope, NEMO — NEutrino Mediterranean Observatory, and NESTOR — Neutrino Extended Submarine Telescope with Oceanographic Research.

were rapidly developed, and they have already given a number of outstanding results, such as the detection of the neutrino radiation burst accompanying a supernova (SN 1987a) explosion in the Large Magellanic Cloud, the establishment of the restriction on the proton lifetime, the study of solar neutrinos and detection of neutrino oscillations, and the reliable observation of the first events produced by neutrinos created in the decay of uranium and thorium series radionuclides in the interior of Earth.

The development of the deep-sea area was initiated about 15 years later and gathered momentum rather slowly because of the unusual engineering problems encountered in solving the issues of the stationary installation of recording instruments at large depths in natural basins or in ice and in the construction of stable systems for data control and transmission. The history of the development of this area of research up to the present time is traced in Table 1.

In this table listing the created, operating, and projected large-scale neutrino telescopes, the DUMAND (Deep Underwater Muon and Neutrino Detection) project, well known in the past, is absent. This project for the construction of a deep-sea Cherenkov high-energy neutrino detector with an efficient volume of about 1 km^3 or more in the Pacific Ocean near the Hawaiian Islands was actively discussed in 1970s–1980s by physicists in the USA, USSR, Japan, and West Germany. On the initiative of outstanding American physicists F Reines and J Learned, the world community began to discuss particular ways for realizing Markov's idea. The technical possibilities were studied for the installation of recording instruments at a depth of about 5 km in the ocean for obtaining reliable information on the energies and propagation directions of neutrinos or, more exactly, charged particles created in the interaction of neutrinos with the target material (i.e., oceanic water). The first deep-sea recording modules based on large-cathode-area photomultipliers were developed and fabricated. The strings of such modules submerged from a ship were tested as the base element of a future detector; however, attempts to install the string at the ocean bottom for operating in the stationary regime failed. The researchers had no time to overcome the encountered deep-sea engineering problems because they lost credit from financers, and for this reason the project was closed down in the mid-1990s.

The direct participation of Soviet physicists and oceanologists in this project ended much earlier, about 1980, which was related to the well-known events in Afghanistan. At the suggestion of A E Chudakov, supported by M A Markov, a start was made on the development of the method for deep-sea neutrino recording in Lake Baikal as a proving ground for testing and constructing the prototypes of future large-scale detectors. The first deep-sea NT-200 detector was constructed in Baikal over the period between 1993 and 1998, and the first events produced by neutrinos were detected in 1994. By 2005, the effective detector volume was increased to 10^7 m^3 due to the installation of the external strings of deep-sea recording modules. To date, the scientific and technical project has been developed and the program for testing the basic elements of the NT-1000 [Baikal-GVD (Gigaton Volume Detector)] detector with the effective volume of about 1 km^3 is being completed [2]. The results of investigations performed with the NT-200 and NT-200 + detectors and the story about basic elements of the project of the future NT-1000 detector are presented in this report.

In concluding the story of work on the DUMAND project, the first and rather adventurous head-on storm of the problem, it is necessary to emphasize that this experience proved to be far from useless. On the one hand, this project has distinctly demonstrated the difficulties encountered in the deployment of stationary systems in natural basins, and, on the other hand, many problems regarding the construction of deep-sea recording instruments have been solved and theoretical studies of the problems of high-energy neutrino astrophysics have been developed. All this initiated the formation of the NESTOR, ANTARES, and NEMO research groups setting as a goal the drawing up of the projects and the creation of large-scale detectors with an effective volume of about 1 km^3 in the Mediterranean Sea [3], and as the intermediate stage, the creation of detectors with a volume of about 10^7 m^3. The ANTARES collaboration advanced more than the others and completed the deployment of the first such detector in Toulon Bay near the French coast in 2008 [4] (see Table).

The idea of creating large-scale detectors with recording instruments located directly in a transparent natural medium, being initially a purely 'deep-sea' idea, acquired a new sense in the early 1990s, after the ingenious proposal of J Learned and

F Halzen to locate the equipment in deep layers of Antarctic ice. The optical properties of ice at depths of more than 1.5 km proved to be adequate for solving this problem, and the AMANDA detector was constructed at the American Amundsen–Scott South Pole Station in the 1990s [5]. The recording instruments were sunk and frozen into holes specially melted in the ice using a hot water drill. The successful development of the project allowed the researchers to persuade the US Congress to invest about \$300 billion for the construction of the next-generation IceCube neutrino telescope with an effective volume close to 1 km^3 [6]. The drawing up of this project and the construction and assembling of the detector equipment took approximately ten years, and the detector was assembled in accordance with the design version on 18 December 2010. The 'inauguration' of this project is planned for the end of April 2011.

This short introduction is written to demonstrate the background against which the Baikal neutrino project developed and continues to develop. The story about this project is presented below.

2. Baikal NT-200 and NT-200+ neutrino telescopes

We can assume that the Baikal neutrino experiment was initiated on 1 October 1980, when the Institute for Nuclear Research (INR), USSR Academy of Sciences announced its decision to found a Laboratory of High-Energy Neutrino Astrophysics, which later became the core of the Baikal collaboration also including Irkutsk State University, Moscow State University, the Joint Institute for Nuclear Research (Dubna), the DESY-Zeuthen Research Center (Germany), Nizhny Novgorod State Technical University, and St. Petersburg State Marine Technical University. The researchers from Tomsk Polytechnical University, the Russian Research Centre 'Kurchatov Institute', the Limnology Institute, RAS Siberian Branch, the Academician Andreev Acoustic Institute, and a number of other Russian and foreign (Hungary, Italy, France) institutions also participated in the experiment at some of its stages.

Lake Baikal was chosen as a place for the development of experimental studies for the following obvious reasons: good transparency (comparable to ocean water transparency) of deep waters; the presence of places with sufficiently steep shore slopes in which a depth of about 1 km, required for protection from penetrating cosmic rays, is located at distances of 4–5 km from the shore; the presence of an ice crust allowing the mounting of deep-sea instruments and laying down cable communications from it for two months per annum, and a low expected level of the intrinsic emission of deep waters caused by bioluminescence and radioactivity. Based on the experience and results of Baikal studies performed for many years by researchers at the Limnology Institute, Siberian Branch of the RAS, a concrete site was chosen for starting the work — an area of the lake adjacent to the 106th km of the Krugobaikal railway.

The design of the project, the mounting and startup of the detector were preceded by investigations of experimental hydrooptical, hydrophysical, and hydrological conditions in Baikal, which were performed for about a decade. In these experiments, the intrinsic emission of deep waters in the lake, which is caused by the oxidation of particles a few micrometers in size, was discovered. This emission is typical of the Baikal bacteria that dominate in amount and of many phyto- and zooplankton species. In collaboration with the 'Ekran' Special Design Bureau in Novosibirsk, the high-sensitive hybrid Kvazar-370 photodetector with a photocathode 370 mm in diameter was developed exclusively for the Baikal neutrino telescope [7]. Deep-sea pilot Cherenkov detectors were installed for prolonged operation to try out the method of data acquisition and perform the first physical experiments.

The next task of the Baikal collaboration was the construction of the first large-scale deep-sea NT-200 neutrino telescope [8] with an effective detection area of (2–10) $\times 10^3$ m^2 (depending on the particle energy) and carrying out a wide program of physical studies with it. This telescope was assembled and deployed from 1993 to 1998.

2.1 The NT-200 neutrino telescope

The NT-200 telescope, located at a depth of about 1100 m at a distance of 3.6 km from the shore, is connected by bottom communication lines with a shore data control and acquisition center. The telescope represents a three-dimensional lattice of optical modules mounted on vertical load-bearing cables with the lower ends fastened to bottom anchors, and the upper ends fastened to buoys. Each vertical cable with optical modules forms a structural unit of the telescope — a string of optical modules. The telescope contains 192 optical modules mounted pairwise on eight strings, each 68 m in length. The central string is surrounded by peripheral strings located uniformly on a circle 21.5 m in radius (Fig. 1).

An optical module contains a hybrid Kvazar-370 photodetector placed in a low-radioactive glass housing. To suppress the dark counting rate of PMTs and the background emission of the deep waters of the lake, the optical modules are combined in pairs and are switched in a coincidence circuit, detecting signals within a time window of ~ 15 ns. Two pairs of optical modules, having a common electronic system module, form a functional unit of the string,

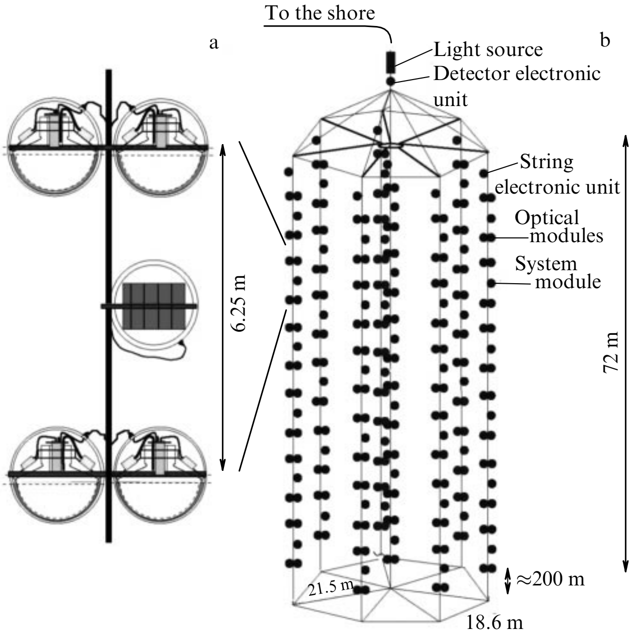

Figure 1. (a) Structural element of the NT-200 telescope ('bundle') consisting of two pairs of optical modules connected in a coincidence circuit and an electronic module providing their operation. (b) Schematic of the NT-200 telescope.

a 'bundle'. The system module contains two units generating a local signal, an amplitude conversion unit, a light-diode triggering unit, and a control unit. The system module generates the output signals (local triggers) of two bundle channels with durations proportional to input charges and the leading edge determining the channel response time.

Local triggers from all the system modules of a string are fed to the string electronic units (SEUs). These electronic units have six measurement channels, a controller, and modems of the data and control channels. Each string has two SEUs connected with the detector electronic unit (DEU). Information from each measurement channel is digitized in the SEU, a local trigger is generated, and a request signal is formed in the DEU. If a sufficient number of request signals are accumulated in the DEU from string electronic units within a 500-ns time interval, a confirmation signal is generated, which is fed to all the string electronic units. Then, a number is assigned to the event in string electronic units and the data accumulated are transferred to the shore data acquisition and control center.

2.2 The NT-200+ telescope

To increase the efficiency of detecting high-energy neutrinos, the NT-200 telescope was modernized in 2004–2005. The new facility, called NT-200+ neutrino telescope [9], provided both an increased efficient volume for recording cascades produced by neutrinos and a considerably improved telescope energy resolution as a whole. The NT-200+ detector represents the initial version of the structural unit of the future Baikal neutrino telescope with an efficient volume of order 1 km^3.

The telescope consists of the central part (NT-200) and three additional external strings located at a distance of 100 m from the central part of the detector (Fig. 2). Each external string contains 12 optical modules grouped in pairs, similarly to the optical modules of the NT-200 telescope. The distances between the channels of the external strings are 20, 50, 20, 30, and 20 m from the channel top.

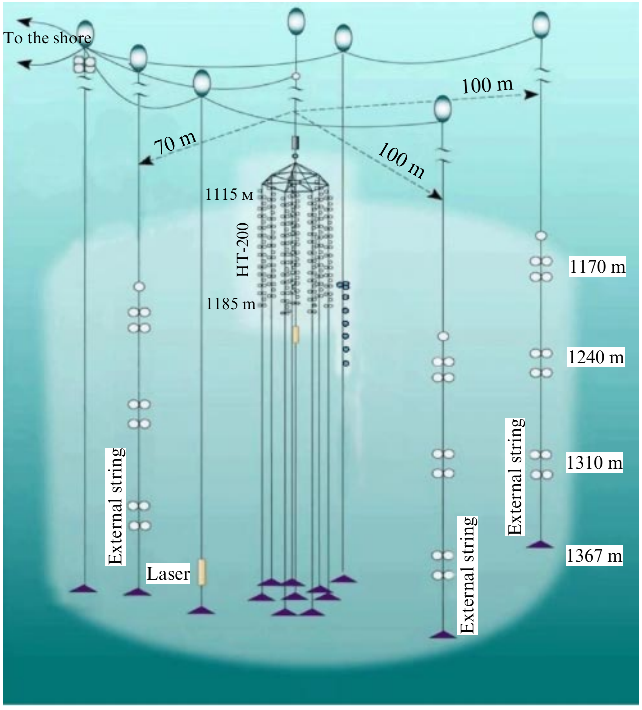

Figure 2. NT-200+ detector.

While optical modules, system modules, and measurement channels of each external string are the same as those in the NT-200 telescope, the electronics of the SEU controller were considerably modernized. Each measurement channel of the SEU contains a time–code converter, a duration–code converter, and an event number recording circuit. A string request signal is formed by the SEU controller for double coincidences of the channel request signals within the 0.5-μs time window. Requests from all the external strings are fed to the central commutation module [data acquisition (DAQ) center], where a confirmation signal is generated and fed back to all the external strings. In the presence of the confirmation signal, information on each local trigger (time, amplitude, event number, measurement channel number, and global event number) is delivered through the SEU controller to the DAQ center. The DAQ center provides the combination of data flows and translation of all obtained information to the shore center.

2.3 Basic results obtained in NT-200 neutrino telescope experiments

The Baikal deep-sea neutrino telescope is one of the three largest high-energy neutrino detectors (along with ICeCube at the South Pole, and the underwater ANTARES detector in the Mediterranean Sea). The important results of the first stage of Baikal project investigations obtained with intermediate setups between 1980 and 1998 concerned both the study of the parameters of detectors and atmospheric muon fluxes, the selection of events produced by neutrinos, and the search for magnetic monopoles. The upper intensity limit for the flux of superheavy magnetic monopoles was found from the catalysis of baryon decay, which was at that time one of the strongest theoretical and experimental restrictions. In experiments with the NT-36 and NT-96 detectors, the first neutrino events were recorded and one of the strongest restrictions on the muon flux was found, which was caused by the annihilation of dark matter massive particles (neutralinos) at Earth's center [10]. In addition, the restriction on the intensity of the superhigh-energy (above 10 TeV) natural neutrino flux was established [11].

The most important results were obtained in 2005–2008 in experiments with the Baikal telescope. The analysis of these experiments has demonstrated the existence of new restrictions (one of the strongest at present) on the intensity of the natural flux of fast ($v/c > 0.8$) magnetic monopoles, 4.6×10^{-17} cm^{-2} s^{-1} sr^{-1} (for $v/c = 1$) [12], on muon fluxes accompanying the annihilation of dark matter massive particles (neutralinos) at Earth's center, 4.2×10^{-15} cm^{-2} s^{-1} [13], and at the Sun's center, 3×10^3 km^{-2} year^{-1}, in the region of neutralino masses above 500 GeV [14], on the neutrino flux from gamma bursts in the energy range up to 10^7 GeV [15], on the neutrino flux from local galactic sources located in the Southern Celestial Hemisphere depending on the declination, $E^2F < 5 \times 10^{-10}$ TeV cm^{-2} s^{-1}, and, finally, the restriction on the intensity of the natural diffusion neutrino flux, which is $E^2F < 2.9 \times 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} for the total flux of neutrinos of all types in the energy range from 2×10^4 GeV to 2×10^7 GeV and lies in the region of theoretically predicted values [16]. In addition, the strongest at present restriction $F < 3.3 \times 10^{-20}$ cm^{-2} s^{-1} sr^{-1} GeV^{-1} on the electron antineutrino flux in the region of the

6.3×10^6-GeV resonance was established [17]. The implementation of the NT-200+ detector project provided approximately a threefold increase in the sensitivity of experiments on searching for the natural diffusion neutrino flux and made it possible to begin the study of their energy spectrum at energies up to 10^{18} eV.

The fortunate combination of natural factors along with the well-studied place for experimentation and the experience acquired in the deployment and operation of the first-generation NT-200/NT-200+ neutrino telescope provided the required prerequisites for the beginning of work on the designing and construction of the deep-sea Baikal NT-1000 neutrino telescope with an efficient volume of order 1 km^3.

3. The NT-1000 neutrino telescope (Baikal-GVD)

The successful operation of NT-200/NT-200+ and AMANDA neutrino telescopes for more than ten years and the results obtained in these experiments stimulated the development and building of next-generation telescopes IceCube, NT-1000, and KM3NeT with characteristic scales on the order of 1 km^3. The Baikal NT-1000 telescope and Mediterranean KM3NeT telescope both located in the Northern Hemisphere and the IceCube telescope located at the South Pole will supplement each other due to their different geographical positions, and will form the world network of telescopes for searching for and studying neutrino sources in the entire celestial sphere. Detectors located in the Northern Hemisphere have an important advantage because they can perform virtually continuous observation of the Galaxy center and galactic plane where a significant part of the potential sources of high-energy cosmic rays are concentrated.

The deep-sea NT-1000 neutrino telescope [2] is intended for solving a variety of problems in astrophysics, cosmology, and elementary particle physics: the search for local neutrino sources, the study of the diffusion neutrino flux, the search for dark matter manifestations, and the search for magnetic monopoles and other hypothetical particles. The next-generation deep-sea Baikal NT-1000 telescope will be an experimental complex intended to study natural neutrino fluxes at energies above 10 TeV by detecting the Cherenkov radiation of secondary muons and showers generated in neutrino interactions.

The concept of the NT-1000 neutrino telescope is based on a number of quite obvious requirements for the construction and deployment of the recording system of the new detector: the maximum possible use of the advantages of mounting the recording system from the ice crust of Lake Baikal; the possibility of building up the facility and providing its efficient operation already at the first stages of deployment, and the potential of using different variants of the arrangement and number density of photodetectors within one measuring system.

Taking into account the requirements mentioned above and estimates of the sensitivity and energy resolution of the NT-1000 neutrino telescope obtained in the large-scale simulation of the telescope response to Cherenkov radiation from muons and showers, the architecture of the measurement and communication systems was developed and the basic configuration of the telescope was chosen (Fig. 3). Radiation is detected with 2304 Hamamatsu-7081HQE photomultipliers with a hemispherical photocathode 250 mm in diameter. Photomultipliers, together with control electronics, are encased in deep-sea glass housings, forming optical modules. The optical modules mounted on vertical cables form strings.

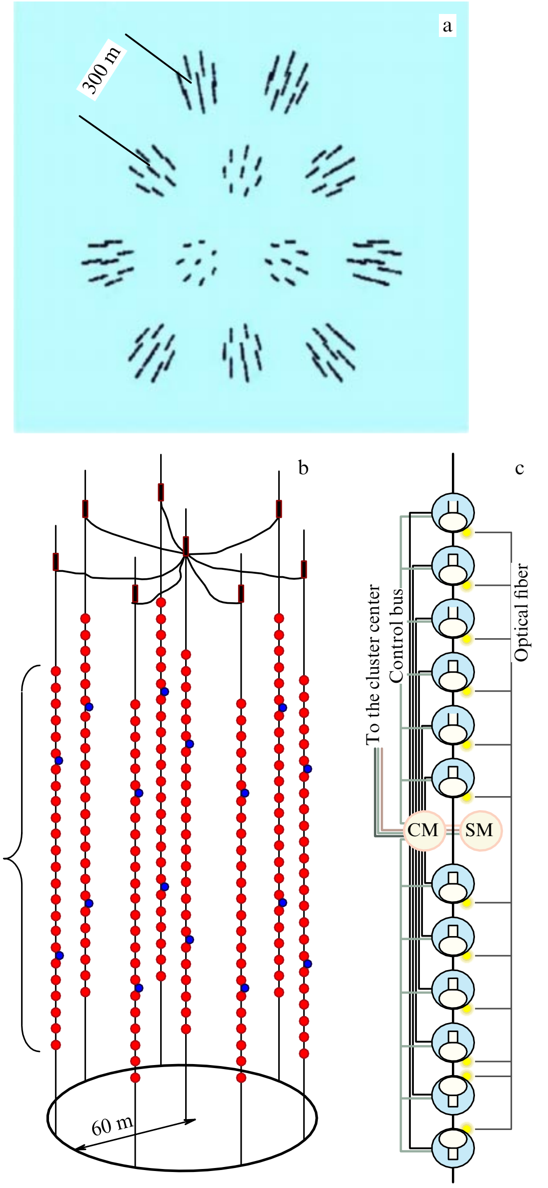

Figure 3. Schematic view of the km3-scale NT-1000 neutrino telescope in Lake Baikal: (a) top viw; (b) telescope cluster; (c) string of optical modules.

The basic structural unit of a string is the section of optical modules. The section comprises a functionally complete detector unit including systems for radiation detection, signal processing and calibration, trigger formation, and data transfer. The section contains 12 optical modules arranged 15 m apart along the string, and the central and service modules. Analog signals from all optical modules of the section are fed to the central module over coaxial cables. The low-voltage supply is fed to optical modules over the same cables. The analog signals from optical modules are converted in the central module to a digital code and information is transferred over an Ethernet line. The service module is designed for calibrating the time channels of the setup, and determining the string position and electrical feeds of the optical modules. The string position is determined with a hydroacoustic coordinate measurement system. The synchronization, power supply, and data transfer channels of the sections are combined in the switching module of the string, which is connected with the central control unit of a cluster.

The basic configuration of each of the 12 clusters in the NT-1000 neutrino telescope contains eight strings, each including 24 optical modules (two sections in a string) separated from each other by 60 m. The distance between adjacent clusters reaches 300 m. The string clusters are connected with the shore center by combined electrooptical cables about 6 km in length. Each cluster of the NT-1000 telescope is a functionally complete detector (with the detection volume on the scale of NT-200+ or ANTARES detector), which can operate both incorporated into the setup and independently. This provides the simplicity of expanding up the telescope instrumented volume and the possibility of bringing into operation its separate parts during the deployment of NT-1000.

The basic configuration of the telescope provides an efficient volume of 0.2–0.7 km^3 for recording showers in the energy range from 10^5 to 10^9 GeV, and an efficient area of 0.2–0.5 km^2 for recording muons in the energy range from 10^4 to 10^6 GeV. The accuracy of recovering the muon propagation direction ranges $0.4° - 0.6°$, and that for showers is $5° - 7°$. The relative accuracy of the shower energy recovery comes to 20–35%.

Long-term full-scale tests of the equipment of the NT-1000 section were successfully performed in Lake Baikal between 2008 and 2010. A prototype of the NT-1000 cluster was already constructed and tested under laboratory conditions and will be deployed in Lake Baikal in the continuous data acquisition regime during the winter expedition in 2011.

4. Conclusions

Thus, the method of deep-sea recording of elementary particles (and its ice modification) proved its efficiency for studying natural high-energy neutrino fluxes. The modern knowledge of the diffusion neutrino flux in the energy range from 10^{13} to 10^{18} eV, local sources of neutrinos with energies above 10 GeV, the natural flux of fast magnetic monopoles, and dark matter massive particles manifestations is mainly determined by the results of experimental studies performed with the Baikal NT-200/NT-200+ neutrino telescope, the AMANDA detector at the South Pole, and (in late 2009 and 2010) the ANTARES detector in the Mediterranean Sea. Bringing the IceCube detector into operation at the South Pole will provide the increase in the sensitivity of some experimental studies by one–two orders of magnitude.

On the agenda is the problem of the construction of a detector (or detectors) in the North Hemisphere for studying the center of our Galaxy with a sensitivity comparable to that of the IceCube detector. The Baikal collaboration, which developed, constructed, and prepared for full-scale tests a prototype of the basic element — an autonomous cluster of deep-sea strings of recording modules for the km3-scale NT-1000 detector (Baikal-GVD) — is considerably ahead of all on the part to constructing the operating project of such a detector.

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Telescope Array Observatory observations of the Greisen–Zatsepin–Kuzmin effect

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1. Introduction

The enigma of the origin of ultrahigh-energy cosmic rays (UHECRs) is one of the most interesting and important unsolved problems of particle astrophysics. The center of attention in this research field is the Greisen–Zatsepin–Kuzmin (GZK) effect. Recently, the Telescope Array (TA) observatory, the largest observatory in the northern hemisphere of Earth, studying the origin of UHECRs, began to operate in the state of Utah (USA). In this report, we consider the fundamentals of the GZK effect, its history and present observational status, and preliminary results obtained at the

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