Baksan Neutrino Observatory of the INR RAS: current state and prospects

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Abstract An overall view of the Baksan Neutrino Observatory of the INR RAS infrastructure is presented. Ground-based and underground facilities used to study cosmic rays, rare nuclear reactions and decays, to register solar neutrino, to observe various geophysical phenomena are described. Some main results obtained with these facilities and prospects are given.

Keywords: Underground Physics, Neutrino, Supernovae

The Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences (BNO INR RAS) is situated at the foot of the Andyrchy Mountain in the Baksan valley of

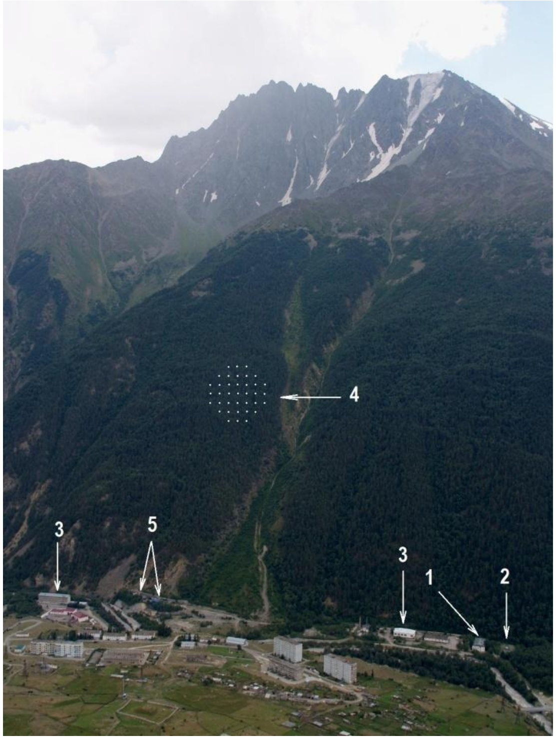

Fig1. *The overview of BNO INR RAS and Neutrino village: 1) the "Elling" building with "Carpet" detection facility; 2) the shallow underground hall with "Carpet-2" detection facility; 3) laboratory's buildings; 4) the schematic view of "Andyrchy"-array at the mountain slope; 5) entrances to the "Main" and "Auxiliary" adits.*

Kabargino-Balkarian Republic of the Russian Federation. The Observatory is intended for carrying out investigations in the fields of the cosmic rays physics, neutrino astrophysics and non-accelerator nuclear physics [1], [2]. The Observatory comprises a series of ground-based and underground installations. The overview of BNO INR RAS and Neutrino village is shown in Fig.1.

The ground-based complex of BNO INR RAS

1. “Carpet”

In 1973 the first facility of the Observatory came into operation. It was the ground-based detection facility “Carpet” composed of 400 standard scintillation detectors situated in the experimental hall called “Elling” [3]. Each detector is a rectangular aluminum tank (70 cm·70cm·30cm) filled with liquid scintillator on the base of white spirit (a high purity kerosene fraction of petroleum). Each tank is viewed by PMT (15 cm in diameter) through a viewing port mounted on the central round hole of the larger face of the tank. Analysis of the amplitude distribution of signals and of their delay in arrival to the registering device allows one reconstructing the spatial distribution and direction of particles of an extensive air shower. This ground-based facility of 200 m^2 shown in Fig.2 is an exact replica of the eight-layer one of the Baksan Underground Scintillation Telescope that came into operation later.

Fig2. *The overview of the “Carpet“ facility.*

The “Carpet” facility was targeted to study primary cosmic rays of $5.7 \cdot 10^9 \div 10^{16}$ eV, mechanisms and characteristics of their interaction with particles of the atmosphere by registering a single secondary component together with EAS generated in such interactions. Six outdoor points, each containing nine scintillation detectors, have been added to the central multiple-unit detector. Four of these points are distributed symmetrically on a circle of 30 m radius, and two points are on a circle of 40 m radius with regard to the “Carpet”’s center. A neutron monitor in a separate compartment of the basic hall is targeted to register neutrons generated by cosmic rays.

"Carpet" (now "Carpet-2" [4]) performance was significantly improved after coming into operation in 1998 of one section (the middle one) of the three-sectioned large underground Muon Detector facility (MD). The middle section is at ~ 40 m from the "Carpet"'s center. MD is under 2 m layer of the ground (5 m w.e.) which absorbs the soft c.r. component and is composed of 175 scintillator detectors (1 m^2 each and made of plastic scintillator of 5 cm thickness). The continuous registering area of the facility is 175 m^2 (5 m × 35 m). The threshold energy for muons is 1 GeV. The sensitivity of the facility is 0.006 particles/m^2. The creation of "Carpet-3", the advanced version of "Carpet-2", is now in progress. It is supposed to be a multipurpose facility registering cosmic rays. Its main purpose would be to study the knee of the c.r. spectrum. "Carpet-3" would register the following components of EASs: 1) electron and photon; 2) muon (with a threshold of 1 GeV); 3) hadron [5].

Analysis of the obtained data allowed one to interpret the presence of multi-jets showers as a result of generation of streams of particles with large transverse momentum, and to evaluate the cross-section of this process in hadron-hadron interactions for the range of energies up to 500 GeV [6]. This experimental result was the first one to confirm quantum chromodynamics predictions and was published before the SPS-collider in CERN had measured this value.

Large counting rate of single muons from cosmic rays (~ $4.3\cdot10^4$ s^{-1}) allows high statistical accuracy even for small time intervals (0.003% for 4 min) and, as a consequence, makes it possible to observe short-time periodic variations (micro-variations). None of these have been found with the "Carpet" array at a confidence level of 0.001%. During this research work a new type of sporadic temporary variations characterized by small time was discovered and attributed to meteorological effects [7]. Their strong correlation with the electric field of atmosphere (such variations occur only during thunderstorms) allowed one to explain this phenomenon and quantitatively describe it [8]. The gigantic increase of cosmic ray intensity during powerful solar burst on September 29, 1989 is one of the most interesting examples of temporary variations in the muon counting rate. Particles of solar origin with energies up to 10^{10} eV were observed for the first time in such an event, and it was the "Carpet" facility that provided the most evident and accurate data at that time [9].

Studying showers of low energy corresponding to primary cosmic rays (c.r.) of 10^{13} eV revealed anisotropy of the latter. The first and second harmonics have been found in the count rate of these showers for sidereal time. C.r. anisotropy for 10^{13} eV was calculated to be 0.05 ± 0.005% [10].

Air showers of $\geq 10^{14}$ eV are continuously registered and the data are analyzed along several lines: search for point sources of gamma-quanta of the same energy [11]; search for signals from extended gamma-ray sources (mainly in the galactic plane) [12]; search for c.r. anisotropy at these energies [13]; search for x-ray and gamma-ray bursts for known sources [14]. One of the interesting results is the registration of the burst in Crab Nebula, on February 23, 1989. It was the team of scientists of "Carpet" that first published the result [15]. Later it was confirmed by teams of Kolar Gold Mine (India) and EAS Top (LNGS) facilities.

Studying air neutron flux variation involves continuous recording of neutron monitor count rate; the data obtained are sent across internet to www.nmdb.eu-nest-seach.php. Analysis of the parameters of variations presents information used in further studies of characteristics of solar bursts and their effect on the interplanetary magnetic field.

The "Carpet-2" facility allows studying EAS muon component. The dependence of the mean number of muons of ≥1GeV (N_μ) registered by MD on the total number of EAS particles (N_e) has been found as $N_\mu \sim N_e^\alpha$, where $\alpha = 0.8$. Analysis of the data obtained with MD and "Carpet" allowed scientists to significantly increase the sensitivity of the experiment searching for local sources of ultra high-energy gamma-quanta, to start studying chemical composition of primary cosmic rays of $E \geq 10^{14}$ eV, and to carry out investigation of variations of muons with energies above 1 GeV [16].

2. “Andyrchy”-array

In 1996 the “Andyrchy “ array targeted to register EASs with $E_0 \geq 10^{14}$ eV came into operation. It consists of 37 standard detectors of the same type as those of “Carpet-2” (1 m^2 each, plastic scintillator) evenly spread over the area of 45.000 m^2 on the slope of the Andyrchy mountain with a maximum gradient of altitude of 150 m and at a distance of 40 m from each other [17]. The central detector of “Andyrchy” is located over BUST, and a vertical thickness of mountain rock separating them is 350 m. It is important to secure the performance of a facility located on the mountain slope during periods of thunderstorm activities. This task has been successfully solved by registering pulses of electromagnetic oscillations generated in lighting discharges. As the increase in amplitude of the pulses with thunderstorm approaching reaches a specified threshold, the electrical network (at the point where the data are collected) automatically disconnects to form short segments, which are switched off from the detector and are re-loaded to the dischargers. The network configuration resumes its functioning after the thunderstorm is over [18].

The following researches are carried out at “Andyrchy”: anisotropy of cosmic rays with $E_0 \geq 10^{14}$ eV [19]; search for gamma-ray bursts with hard energy spectrum [20] and search for of evaporating Primordial Black Holes [21].

The “Andyrchy” array and BUST is a complex of two facilities, situated one upon the other. It is used to study the primary cosmic ray spectrum and its composition in the energy region of the knee, a change in the spectral index at about $3 \cdot 10^{15}$ eV [22].

The underground complex of the BNO INR RAS facilities

Schematic view of a longitudinal section of the BNO adit and Andyrchy slope is shown in Fig.3 presenting the locations of different underground laboratories and the dependence of underground muon flux on the distance from the entrance. Descriptions of the laboratories are adduced below.

1. The Baksan Underground Scintillation Telescope

The Baksan Underground Scintillation Telescope (BUST) has come into operation in 1978. It was targeted to solve various tasks in astrophysics, cosmic rays physics and elementary particle physics [23]. BUST is situated in the underground hall of ~ 12.000 m^3 at a distance of 550 m from the entrance to the underground horizontal tunnel. The effective thickness of the ground above BUST is 850 g/cm^2. The telescope is a rectangular building of 11.1 m height and 280 m^2 base. The blocks of the building are made of low-radioactive concrete. Its four horizontal and four vertical planes are covered with standard scintillation detectors (3180 in total). The total mass of the telescope is 2500 t, that one of the scintillator is 330 t. Signals are taken from each of 3180 standard scintillation detectors and processed in the same way as those of the “Carpet” array. The threshold of integral discriminator corresponds to energy release of 10 MeV in the detector. Signals from individual "A - T" converters, from integral discriminators, and anode signals from a group of detectors from each of 8 layers of the telescope go to the registering devices in the apparatus hall. Analysis of the signals allows one to determine the coordinates of the detectors through which particles have passed and their arrival directions. The information from registering devices together with that of absolute- and relative-time systems goes via a direct channel to DAS (data accumulation system). Every 15 minutes the collected information that has been preliminary processed goes through the optical fiber to the BUST server. About ten diagnostic programs are running simultaneously providing information on the performance of all the systems of the telescope.

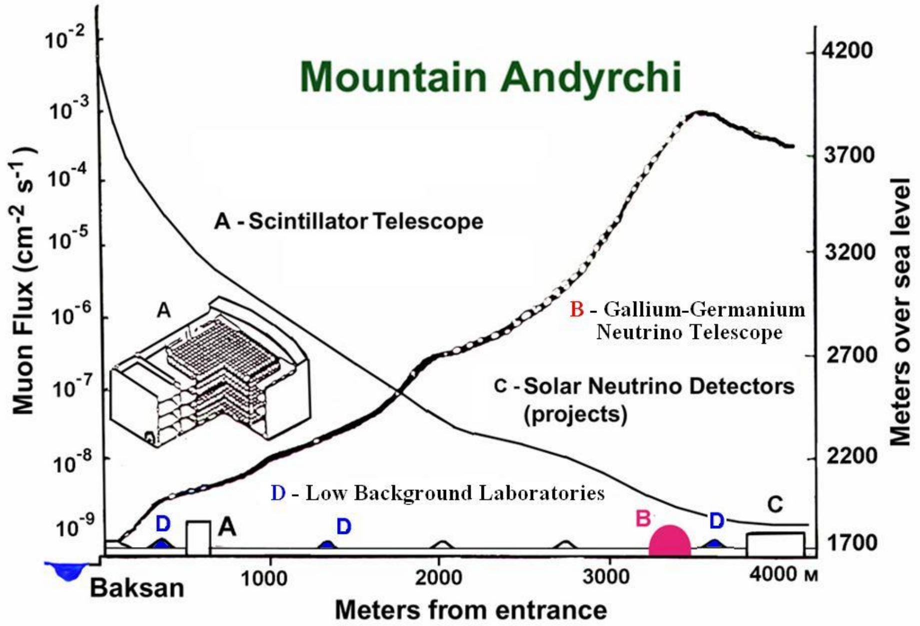

Fig3. *Schematic view of a section of the Andyrchy slope along the adit (right scale) and dependence of underground muon flux on the laboratory location depth (left scale).*

Though relatively small, the thickness of the mountain rock above the telescope reduces the background caused by c.r. by 3600 times in comparison with that on the surface (the count rate of single muons with $E>0.2$ TeV is 12 s^{-1}). The reduced c.r. background allows scientists to study problems related to rare processes registration, such as-measurement of the muon flux generated by high-energy neutrino; search for neutrino bursts accompanying a star collapse in the Galaxy, and others. At the same time, the residual c. r. intensity in the underground environment allows one to carry out a research into a wide range of tasks of cosmic ray physics: anisotropy of c.r. of $>10^{12}$ eV, chemical composition of primary c.r. of $10^{12}\div10^{16}$ eV, interaction of muons of >1TeV with matter, and others.

The following are the most important results obtained over the years of research:

- muon flux generated by atmospheric neutrino of cosmic rays in the rock under BUST has been measured to be $I_\mu^\nu = (2.60 \pm 0.15)\cdot10^{-13}$ cm^{-2}s^{-1}sr^{-1} [24];
- one of the first limits obtained for the oscillation parameters of atmospheric neutrinos of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ types [25];
- a limit on high-energy neutrino flux from local sources in the galactic plane;
- the best limit, for a time, on the slow and heavy magnetic monopoles $P \leq 5.5\cdot10^{-16}$ cm^{-2}s^{-1}sr^{-1}] [26];
- the amplitude $(12.3\pm2)\cdot10^{-4}$ and the phase 1.6 ± 0.8 (in sidereal time) of the first harmonic of c.r. anisotropy have been measured [19];
- data accumulated during 34 years (live time 29.8 years) of monitoring the Galaxy in studying neutrino bursts from gravitational stellar collapses gave a limit on the frequency of bursts f to be $f < 0.077$ yr (90% C.L.) [27];
- neutrino flux from SN1987A that collapsed in the Large Magellan Cloud was registered simultaneously with USA, Italy and Japan facilities [28];

- proton stability had been tested in 1981-1983 years and the limit for the half-life of proton was achieved: $T_{1/2}>0.9\cdot10^{31}$ years [29];
- the data obtained in studying of chemical composition of primary c. r. of 10^{13}-10^{15} eV are in good agreement with the results of direct measurements for lower energies (10^{12} eV) [30];
- the technique to separate hadronic and electromagnetic cascades, based on registration of π-μ-e-decays accompanying the cascade, has been developed and realized in an experiment [31];
- total cross-section of hadronic photoabsorption has been measured for photons with energies up to 10 TeV [32];
- the experimental data on cross-section of γ-N interaction for the range of energies of 40 - 130 GeV have been obtained using the measured value of the nuclear cascades fraction. These data together with those obtained at DESY's HERA collider, confirm the effect of more rapid growth of cross-section of photon-hadron interaction than that of hadron-hadron interactions [33].

A set of preparatory and research works is carrying out at the BNO INR RAS at present time directed to a development of a project of a large liquid scintillator detector with a mass of 5-10 kt which could be built at the ~4000 m w.e. depth. The detector is intended for the investigations of the neutrino and antineutrino fluxes from different natural and artificial sources such as decays of the radioactive elements in the Earth, thermo-nuclear reactions in the SUN, super-nova bursts, nuclear reactors and others.

2. Low-background Laboratories

Low-Background Laboratories (LBL) carry out research of extremely rare reactions and decays with energy release up to 4 MeV. For these studies one needs to diminish not only the background caused by cosmic rays but also that one due to the decay of natural radioactive elements always present in the environment. The latter task has been solved by screening the experimental underground facility with a combination of layers of ultrapure shielding materials absorbing radiation, and by making sure that the facility is made of ultrapure material. The researches carried out in the LBL are search for various modes of double beta-decay of a number of isotopes; search for candidate-particles for dark matter of the Universe; test of the law of electrical charge conservation and many others.

There are three underground laboratories, situated at a different depth, where LBL researches are carried out: 1) low-background chamber at a depth of 660 m w.e, 385 m from the entrance to the tunnel, useful area of 100 m^2, put into operation in 1974 [34]; 2) chamber for precise measurements at 1000 m w.e. depth, 620 m distance from the entrance, useful area is 20 m^2, put into operation in 1985; 3) deep underground low-background laboratory (DULB-4900) at 4900 m w.e. depth, 3670 m from the entrance, useful area is 200 m^2, put into operation in 1993, modernized in 2008 [35]. Cosmic ray flux in these three chambers is reduced by $2\cdot10^3$, $8\cdot10^3$, and 10^7, respectively.

A number of low-background facilities based on semiconductor, gaseous and scintillation detectors have been designed, made and used over the years in various experiments such as: study of cosmogenic radioactive isotope distribution in the samples of moonrock brought by Automatic Interplanetary Stations Luna-16, Luna-20 and Luna-24; test of the hypothesis of cosmic ray intensity being permanent during the last several hundreds of thousands of years performed by measuring the content of cosmogenic isotope ^{81}Kr in the atmospheric air [36]; investigation of the radioactive purity of industrial metal and a selection of those to be used in the construction of low-background facilities with the lowest possible natural radioactive contamination [37]; the experiments searching for two-neutrino and neutrinoless double-beta-decay of isotopes of ^{76}Ge, ^{100}Mo, ^{150}Nd, ^{136}Xe [38] – [41]; for 2K-capture in ^{78}Kr and ^{124}Xe isotopes [42], as well as other experiments have been carried out.

A possibility of a creation of the new low-background cryogenic laboratory in the existing cavity at the 2620 m distance point of the Main Adit (~3000 m w.e.) examines in the BNO at present time.

Investigation of 0.01-4000 eV energy-releases from different rare nuclear processes could be done in the laboratory with cryogenic calorimeters having the best energy resolution in comparison with detectors of the other types.

3. Gallium-Germanium Neutrino Telescope

Gallium-Germanium Neutrino Telescope (GGNT) is targeted to measure solar neutrino flux which carries unique information on thermonuclear reactions in the central regions of the Sun as well as on neutrinos themselves. Sine 1986 the experiment has been carried out within the frames of the Soviet American Gallium Experiment (SAGE) [43].

The experiment is based on the reaction ($^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$). The advantage of this reaction is its low threshold of 0.233 MeV. The pp-neutrinos, having energy up to 0.423 MeV and constituting the main portion of solar neutrino flux, can be registered through this reaction. Radioactive isotope, ^{71}Ge produced in this reaction undergoes decay by electron capture, with $T_{1/2}$=11.4 days half-life. Registering ^{71}Ge decays allows one to determine the number of interacting neutrinos and to calculate the solar neutrino flux.

Fig4. *A view of the GGNT hall.*

The underground complex of GGNT laboratories is situated at a distance of 3.5 km from the entrance to the tunnel, at a depth of 4700 m w.e. where muon flux is reduced by 10^7 times due to natural mountain rock shielding, and is $(3.0\pm0.1)\cdot10^{-9}$ $cm^{-2}s^{-1}$. The main hall of this complex is of $60\cdot10\cdot12$ m^3 dimensions. A view of the hall is shown in Fig.4. To reduce the background caused by neutrons and gamma-ray coming from the surrounding natural rocks the hall is encased in concrete of low-radioactivity and steel sheets, of 600 mm and 6 mm thickness, respectively. The flux of neutrons with energies of 1.0-11 MeV in the laboratory is $\leq2.3\cdot10^{-7}$ $cm^{-2}s^{-1}$. The underground complex of GGNT laboratories includes rooms for: analytical chemistry, ^{71}Ge decay registration system, low-background semiconductor Ge-detector and a number of other auxiliary subdivisions. About 50 t of metallic gallium in a melted state is placed into seven chemical reactors. Natural abundance of ^{71}Ga isotope in gallium is 39.6%. Given the expected solar neutrino flux of $6\cdot10^{10}$ $cm^{-2}s^{-1}$, there should be produced 25 atoms of ^{71}Ge during one month of 50 t metallic gallium exposition in the underground conditions. A unique and effective technique (90% extraction efficiency achieved and kept over the years) has been developed to extract ^{71}Ge atoms from the 50 t melted metallic gallium target containing $5\cdot10^{29}$ of ^{71}Ga atoms. The periodicity of this extraction procedure which is the basic technological process of the telescope is 30 days. The gas GeH_4 is synthesized on the base of the extracted stable Ge-carrier atoms added to the target to extract the generated ^{71}Ge atoms. It constitutes the main component of the gas mixture filled the proportional counter to register ^{71}Ge decays in the underground registration system of GGNT during 4 months, thereby covering ≥10 half-life periods of ^{71}Ge. Then, within the period of two months, the background is measured. Data from the proportional counter are transmitted in the on-line mode, via fiber-optic channel, to the local server of the GGNT ground-based laboratory. The whole cycle of operations called a run includes ^{71}Ga-target exposition, extraction of ^{71}Ge, and measurement of ^{71}Ge decays.

The analysis of data obtained in the period of January 1990 - December 2010, yielded $65.1^{+3.7}_{-3.8}$ SNU [44] (1 SNU = 1 interaction per second in the target containing 10^{36} atoms of an active isotope). The result obtained in the SAGE experiment constitutes 51 % from the value of 127.9 ± 8.1 SNU calculated within the frames of the Standard Solar Modal (SSM) BPS08. The SSM value does not take neutrino oscillation into account. This result of SAGE experiment together with the results of other underground experiments registering solar neutrino (Homestake, USA; GALLEX/GNO, LNGS; Kamiokande/SuperK, Japan; SNO, Canada) allows to calculate estimations of :

- pp-neutrino flux that reaches the Earth in the form of electron neutrino (electron flavor), [$(3.4 \pm 0.47)\cdot10^{10}$ cm^{-2}s^{-1}] [44];
- total neutrino flux produced in pp-reactions inside the Sun and reaching the Earth in various flavors (electron-, muon- and tau-neutrino) due to oscillation of original electron neutrino, [$(6.0\pm0.8)\cdot10^{10}$ cm^{-2}s^{-1}] [44].

The experimental value of the total neutrino flux is in good agreement with the one predicted by SSM, $(5.95\pm0.06)\cdot10^{10}$ cm^{-2}s^{-1}.

To test and calibrate the techniques used in the SAGE experiment a ^{51}Cr source of $1.91\cdot10^{16}$ s^{-1} intensity emitting neutrinos of 747 keV (90%) and 430 keV (10%) was used. In this calibration experiment the ratio of the measured rate of ^{71}Ge production to the expected one caused by a source of given activity has been found to be 0.95±0.12 [45].

Another calibration experiment was made with artificial neutrino ^{37}Ar source emitting 811 keV neutrinos of $1.51\cdot10^{16}$ s^{-1} intensity. The same ratio of the ^{71}Ge production rates has been found to be $0.79^{+0.09}_{-0.10}$ [46].

The experiment BEST with the two concentric zones Ga-target and 3MCi artificial ^{51}Cr neutrino source is preparing at the BNO INR RAS now [47]. The goals of this experiment are to search for the short-baseline neutrino oscillation and to test of sterile neutrino hypothesis.

4. OGRAN facility

At a distance of 1350 m from the entrance to the main tunnel, the new laboratory is created to accommodate the Optoacoustic GRavitational ANtenna (OGRAN). The OGRAN facility has been constructed using principles of solid-state and laser interferometer gravitational antennae. Acoustic vibrations of solid-state detector (manufactured in the form of cylindrical aluminum bar with a central axial tunnel) induced by gravity wave are registered by optical resonator Fabry-Perot, whose mirrors are mounted on the far ends of the detector. Low noise of such an optical read-out system allows sensitivity of relative deformation to be of 10^{-18} for the detector of 2.5 t without any cooling procedure. This sensitivity is good enough to detect bursts of gravity wave radiation generated in relativistic cataclysms in the center of our Galaxy (~10 kpc) and its close vicinity (up to 100 kpc) according to optimistic scenarios. OGRAN is the cooperative project carried out by Institute for Nuclear Research of RAS, Institute of Laser Physics of SB RAS and Moscow State University (Sternberg Astronomical Institute-SAI MSU).

Construction of the detector was finished in 2011; its installation in the underground laboratory was finished this year. The detector would come into operation in 2016. Measurements of gravity gradient background are supposed to be performed as search for neutrino and gravity events' correlation using simultaneous data of OGRAN and the BUST BNO.

5. Underground complex of Geophysical Facilities

Environmental parameters of the underground laboratory complex are held within stable limits; vibration and acoustic noises are lowered by many times in comparison with those on the surface. Such underground environment provides necessary conditions to carry out various geophysical researches securing their high sensitivity.

There are three underground geophysical laboratories situated at a different distance from the tunnel entrance and supplied with different measuring devices and instruments:

1) the laboratory of SAI MSU, at a distance of 530-610 m from the entrance to the tunnel; researches of the Earth strains are carried out with the high-sensitivity wide-band laser interferometer [48];
2) the geophysical laboratory No1, at ~1520 m; it is a nearby geophysical complex of the Schmidt Institute of Physics of the Earth RAS having tilt indicators (inclinometers), magnetic variometers, and earthquake detection station at its disposal;
3) the geophysical laboratory No2, at ~4000 m; it is a distant geophysical complex IPE RAS having tilt indicators, magnetometers, gravimeters, thermometers as well as earthquake detection stations pertaining to Geophysical Survey RAS.

Data obtained in geophysical experiments allow scientists to monitor seismic activity in the earth crust related to the sleeping volcano Elbrus which is at a distance of about 20 km from the underground geophysical complex of facilities [49].

Various researches at the Baksan Neutrino Observatory INR RAS are carried out in collaborations with Institutions all over Russia and the world. To name some of them, Kabardino-Balkarian State University, Federal South University, Moscow State University, National Research Nuclear University MEPHI, Schmidt Institute of Physics of the Earth RAS, Pushkov Institute of Earth magnetism, ionosphere and radiowaves propagation RAS (IZMIRAN), Polar Geophysical Institute RAS, Geophysical Survey RAS, Institute of Astronomy RAS, JINR, Kharkov National University (Ukraine), Institute of Nuclear Problems (Cosmic Ray Laboratory, Lodz, Poland), international collaborations AMORE, GERDA and EMMA. All these collaborations significantly increase the efficiency of the Baksan complex of ground-based and underground facilities in solving a wide range of problems in modern science.

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