LARGE-SCALE NEUTRINO DETECTORS

input for the 2020 update of the European Strategy for Particle Physics
from the Institute for Nuclear Research of the Russian Academy of Sciences

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Abstract:

We propose a multi-purpose neutrino observatory comprising two very large detectors solving different problems at the intersection of particle physics, astrophysics and Earth science. Baikal-GVD will work jointly with KM3NET and IceCube in the Global Neutrino Network, aiming at the detection and study of high-energy astrophysical neutrinos. The new Baksan neutrino telescope (NBNT) will inherit from its smaller precursor, Borexino, but will become the only large-scale neutrino detector geographically located in Europe. Thanks to the unique low-background conditions at Baksan, determined by a combination of depth and of location far from artificial nuclear reactors, it will be the best instrument in the world to measure the CNO solar neutrino flux, at the same time addressing a wide range of other problems.

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Comprehensive overview

Development of many areas in modern physics, astrophysics and related fields is closely related to the neutrino studies. Neutrinos may bring the key to the way the Standard Model (SM) should be extended: in fact, it is the neutrino oscillations which violate the SM conservation laws (lepton numbers of individual generations) and give the only laboratory proof of the SM incompleteness. The discovery of the oscillations in the solar neutrinos gave a bright example of the application of astrophysical results to understanding of basic properties of elementary particles. Today, the case for studies at the border line between particle physics and astrophysics, from which the fundamental physics may benefit, is even stronger. Particle physics, nature of astrophysical objects with extreme energy release, mechanisms of stars burning, cosmology of the early Universe, structure formation in the Universe, the internal structure of the Earth and other planets - all these topics require a thorough study of the properties of neutrinos and the creation of new-generation neutrino telescopes. Neutrinos are pinned on hopes for understanding the nature of super-powerful astrophysical accelerators, searching for physics beyond SM, understanding the origin of mass, discovering new types of symmetry. Studies of neutrinos from various sources - reactor, solar, accelerator, galactic, extragalactic, as well as those from high-intensity artificial sources – are currently underway in experimental laboratories in many countries. At the same time, the rapid development of the neutrino theme in the world greatly enhances the requirements for the new-generation neutrino telescopes. First of all, it concerns a significant increase in the mass of the target used to observe the reactions caused by neutrinos and to improve the quality of the information received. Modern installations should provide real-time information with equipment and large-volume targets located deep underground or under a large layer of water or ice protecting them from cosmic rays.

In Russia, we have a long story of neutrino research and a significant potential for future developments in the field. Soviet and Russian scientists have made a fundamental contribution to the modern understanding of the properties of neutrinos (the concept of neutrino oscillations – B.M. Pontecorvo, oscillations in matter – S.P. Mikheev, A.Yu. Smirnov), and in the development and implementation of the concepts of neutrino experiments . The generally accepted method for recording high-energy neutrinos in large volumes of natural water or ice was proposed by M.A. Markov and I.M. Zheleznykh and first implemented in an experiment on Lake Baikal under the direction of G.V. Domogatsky. Today, the renewed Baikal experiment is being actively developed and is, as of 2018, the largest in the Northern Hemisphere. Pioneering work on the registration of lower-energy neutrinos in underground installations is associated with the names of G.T. Zatsepin and A.I. Chudakov. In our country, the world's first deep-level underground laboratory, built specifically for conducting neutrino experiments, the Baksan Neutrino Observatory (BNO), was created. On the Gallium-Germanium Neutrino Telescope (GGNT) BNO in the frameworks of SAGE (Soviet-American Gallium Experiment), the international group led by V.N. Gavrin was the first to measure the integral flux of all solar neutrinos coming to Earth and to demonstrate the deficit of solar neutrinos in the whole range of the energy spectrum, which was an important contribution to the discovery of neutrino oscillations, and also confirmed that thermonuclear reactions are the source of solar energy. Fundamental results in particle astrophysics were obtained using the Baksan Underground Scintillation Telescope (BUST), the first ever multipurpose neutrino detector. Those include the neutrino signal from the 1987A supernova exploded in the Large Magellanic Cloud.

In 2018, the project of the Multi-purpose Neutrino Observatory has been put forward as a potential "Mega-Science" project of the Federal level. The technology of conducting large-scale experiments in neutrino physics imposes various requirements on geographic conditions that are satisfied in different regions of Russia. The study of high-energy astrophysical neutrinos requires the presence of large volumes of clean water (Lake Baikal); for smaller energies, large underground deep-seated laboratories with a developed infrastructure (Baksan Neutrino Observatory, BNO) are needed. For experiments recording neutrinos of low and medium energies of astrophysical and geophysical origin, the key role is played by remoteness from nuclear power plants (Caucasus, including BNO). All this predetermines with necessity the geographically distributed nature of the multi-purpose neutrino observatory. The proposed observatory will include two following basic instruments:

1) The Baikal Deep-Water Neutrino Telescope (Baikal-GVD - Gigaton Volume Detector) for detection of high-energy astrophysical neutrinos;

2) The New Baksan Neutrino Telescope (NBNT, New Baksan Neutrino Telescope), a large-scale underground scintillation detector, the world's largest tool for recording medium-

energy neutrinos and solving problems at the interface of particle physics, astrophysics and geophysics.

The main scientific tasks of Baikal-GVD include:

• Studies of the natural neutrino flux in the energy range above 1 TeV.

• Search for sources and understanding the nature of high-energy extra-atmospheric neutrinos, indications to the existence and unusual properties of which are provided by the data of the IceCube detector since 2013.

• Using the neutrino channel to study astrophysical objects in conjunction with the results of classical astronomy, high-energy astronomy, cosmic ray physics and gravitational-wave astronomy.

• Search for signals from the annihilation or decay of dark matter particles.

Scientific problems that will be addressed by the next-generation scintillator neutrino detector NBNT include:

• registration of neutrinos from the Sun, formed in reactions of capture of protons by C, N, O and F nuclei, and subsequent decay of the formed nuclei (the so-called CNO cycle). Measuring the flux of these neutrinos will make it possible to determine with high accuracy the chemical composition of the solar interior, which is particularly relevant in the context of the modern difficulties of reconciling observations of the chemical composition of the photosphere with helioseismology data (the “new problem of solar neutrinos”);

• measurement of antineutrino fluxes from beta decays of isotopes of natural radioactive families 238U and 232Th, as well as 40K, contained in the Earth's interior. Reliable registration of these particles (geoneutrinos) will make it possible to establish the contribution of energy release from the radioactive decay of these isotopes to the total heat flux of the Earth; test the hypothesis of the occurrence of a chain fission reaction in the center of the Earth by searching for the antineutrino flow from the “georeactor”; to determine the Th/U ratio inside the planet, which would allow to answer a number of topical questions about the internal structure, origin and evolution of our planet;

• registration of the isotropic antineutrino flux accumulated in the Universe as a result of gravitational collapses of the nuclei of massive stars and the formation of neutron stars and black holes;

• study of the dynamics of a supernova explosion by recording the intensity and spectrum of a neutrino flash in the event of a supernova explosion with a collapsing core at a distance of up to 200 kpc;

• registration of the cumulative antineutrino flux from all nuclear power reactors present on Earth. Study of electron antineutrino oscillations;
• search for elementary particles of a new type - sterile neutrinos (at the stage of creating a prototype NBNT).

Solving the above-mentioned large-scale tasks will have a tremendous impact on the development of particle physics, astrophysics and Earth science, since the research will focus on key problems that are not solved in modern science: explaining the origin of neutrino masses and the extension of the Standard Model elementary particles and interactions; an explanation of the nature of the dark matter in the Universe; understanding of mechanisms of astrophysical processes with extreme energy release; solving puzzles related to the internal structure of the Sun and the Earth, etc. Creating the proposed experimental infrastructure will require the development and application of advanced technologies that will have numerous applications.

Baikal deep-underwater neutrino telescope Baikal-GVD.

The Baikal-GVD neutrino telescope is created as a complex laboratory, including specially designed optical, hydrological and sonar equipment, which provides unique data for solving problems of high-energy neutrino astronomy, understanding the nature of processes with extreme energy release in astrophysical objects, but also allows to conduct research in related fields of science and technology: hydrology, limnology, geophysics, ecology, long-term continuous monitoring of the state of the aquatic environment of Baykal. The basis of the telescope is a volume array of 5618 supersensitive optical modules that record the pulses of Cherenkov light, caused by the interaction of relativistic particles with the aquatic environment, and the distributed system (local network) of data collection. The grid of the modules is located at depths from 1350 to 700 m in the southern basin of Lake Baikal at a distance of 4 km from the coast. The geometry of the location and the number of optical modules are optimized for recording astrophysical neutrino fluxes with energies above 1 TeV. It is expected that after reaching the effective volume of the telescope for registering showers of 1 cubic km, several dozen events of interest per year will be recorded.

The project is carried out in two stages. At the first (up to 2020) stage, the already existing installation (3 clusters) is expanded to a working volume of 0.4 cubic km (8 clusters) with simultaneous data collection on the equipment put into operation; in the second stage (2021-2025), the working volume will be increased beyond 1 cu. km (20 clusters). The project is being carried out by a collaboration of 9 scientific and educational Russian, international and foreign organizations: INR RAS, JINR, NIIPF IGU, NNGTU, JV GMTU, SINP MSU, Evologics GmbH (Germany), Comenius University (Slovakia), Czech Technical University in Prague (Czech Republic). The composition of the project participants will be expanded during its implementation. Supervision of the quality of the project is carried out by the Technical Committee and the International Observatory Committee, consisting of eminent Russian and foreign experts in this field.

The most important advantage of Baikal-GVD, in comparison with the IceCube neutrino telescope (the best instrument of this type today using the Antarctic ice as a target), is its high angular resolution in determining the direction of motion of the neutrino, which is caused by the difference in the optical properties of fresh water and ice. In particular, for the neutrino registration mode based on the detection of secondary showers, the accuracy of determining the neutrino direction in the Baikal-GVD neutrino telescope will be 3–4 degrees, compared to 10–15 degrees in the IceCube. This corresponds to an increase in the accuracy of the positioning of local neutrino sources by more than an order of magnitude compared to the IceCube and opens up the possibility for the formulation and solution of problems of neutrino astronomy using the shower neutrino detection mode. The neutrino telescopes planned for deployment in the Mediterranean (KM3NET) and the Baikal-GVD telescope will have comparable characteristics in solving problems of neutrino astronomy and astrophysics. The IceCube detectors at the South Pole, the Baikal-GVD and the Mediterranean detectors are integrated into the GNN (Global Neutrino Network) global network, which allows you to search for neutrino sources in the entire celestial sphere. As of 2018, three clusters of the Baikal-GVD telescope were commissioned, which already provided us with a leading position in the creation of large-scale neutrino telescopes in the Northern Hemisphere.

The new Baksan neutrino telescope (NBNT), a large-volume underground scintillation detector.

It is proposed to create a multipurpose large-volume neutrino detector based on a liquid scintillator with a target mass of 10 kt in the Baksan Neutrino Observatory of INR RAS (Kabardino-Balkaria Republic of the Russian Federation), designed to register neutrinos and antineutrinos from the Sun, Earth and astrophysical sources. A large-volume scintillation detector will be located in an underground tunnel at a depth of 4760 m water equivalent. The NBNT detector will have a three-zone design. The central zone, which serves as a target for neutrinos, will be filled with an ultra-pure liquid scintillator (linear alkyl-benzene) and surrounded by a second zone, filled with a non-scintillating organic liquid to suppress the photo-detectors' own background. Photo detectors (photomultiplier tubes and/or silicon photodiodes) will be installed on the surface of the second zone. The outer zone, filled with water and viewed by its own system of photo detectors, will serve for fixing residual background events caused by cosmic particles by the Cherenkov radiation (anti-coincidence method). Being the most sensitive in the world for solving the "new problem of solar neutrinos", the instrument will become one of the key participants in the worldwide network of multi-purpose neutrino detectors of the new generation, which will include the currently created installations HyperKamiokande (Japan), JinPing (China), JUNO (China) , SNO + (Canada). The joint operation of a network of such facilities is important for studying the neutrino signal from the earth's interior. Of the applied tasks that can be solved with the help of a network of large scintillation detectors, one should note the important task for the IAEA for controlling the operation of nuclear reactors. The key advantage of the Baksan location for the detector is the world's lowest (among underground labs) background of neutrino from nuclear reactors, combined with one of the largest underground depths to shield from atmospheric muons.

Currently, RnD works, including the construction of the very first prototype with a 1-ton target, are ongoing. At the next stage of the project, a larger-scale (100 ton) prototype will be constructed. This instrument is considered as a potential target for an experiment to search for eV-scale sterile antineutrino from an artificial source, analogous to the SOX experiment planned some time ago at Borexino but never realized.

To summarize, we propose a multi-purpose neutrino observatory comprising two very large detectors solving different problems at the intersection of particle physics, astrophysics and Earth science. Baikal-GVD will work jointly with KM3NET and IceCube in the Global Neutrino Network, aiming at the detection and study of high-energy astrophysical neutrinos. NBNT will inherit from its smaller precursor, Borexino, but will become the only large-scale neutrino detector geographically located in Europe. Thanks to the unique low-background conditions at Baksan, determined by a combination of depth and of location far from artificial nuclear reactors, it will be the best instrument in the world to measure the CNO solar neutrino flux, at the same time addressing a wide range of other problems.