The multi-messenger astronomy: experiments in the Baksan Neutrino Observatory

V. B. Petkov[1,2]

[1]*Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect, 7a, 117312 Moscow, Russia; vpetkov@inr.ru*

[2]*Institute of Astronomy of the Russian Academy of Sciences, 48 Pyatnitskaya St., 119017, Moscow, Russia*

Abstract An overview of current and future experiments in the field of multi-messenger astronomy at experimental facilities of the Baksan Neutrino Observatory is presented. Different types of these experiments are discussed.

Keywords: Multimessenger Astronomy, Neutrino, Gamma-Ray Bursts, Primordial Black Holes

1. Introduction

Because the high-energy sky has revealed a large number of powerful astrophysical objects capable to emit radiation across the entire electromagnetic spectrum the multi-messenger approach is widely applied now for the study of astrophysical objects and transient phenomena. It is obvious that the joint study of different “cosmic messengers” (cosmic rays, neutrinos, photons, and gravitational waves) is necessary for the complete understanding of the most energetic phenomena in the Universe.

Multi-messenger observations can be conditionally divided into 3 types. To the first type we attribute independent measurements of different messengers which physically are closely connected. (e.g. gamma-rays and neutrino). The synchronous observations of astrophysical objects by means of different messengers relate to the second type. The third type corresponds to the fast response astronomy observations, namely, the quick search of other messenger partners after the alert. All three types are practically accessible to experimental facilities of the Baksan Neutrino Observatory.

The Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences (BNO INR RAS) is one of the centers, in which the research in this direction is being conducted. The observatory is located in the North Caucasus in the Baksan River valley (the geographic coordinates are 43.28° N and 42.69° E, the effective rigidity of geomagnetic cutoff is 5.7 GV). BNO has a unique set of surface and underground experimental facilities, which have been used for the research in the area of the fundamental physics for more than forty years [1]. The research program of the observatory was constantly expanding as new ground and underground setups were put into operation.

2. Complex of experimental facilities

The complex of experimental facilities used in the multi-messenger astronomy studies consists of the Baksan Underground Scintillation Telescope (BUST) and the “Andyrchy” and EAS “Carpet-2” (“Carpet-3”) arrays.

The BUST is located in an underground laboratory under the slope of the Andyrchy Mountain at an effective depth of 850 m.w.e.; its height above sea level is 1700 m [2, 3]. Its size is 17×17×11 m^3 and it consists of four horizontal and four vertical scintillation planes. The planes of the telescope are covered with scintillation counters, the total number of which is 3184. A standard scintillation counter of BUST is an aluminum container of a size of 0.7×0.7×0.3 m^3 filled with liquid whitespirit-based organic scintillator. The scintillator volume is viewed by a FEU-49B photomultiplier with a photocathode diameter of 15 cm. The most probable energy release in the counter from muons is 50 MeV. The DAQ system is triggered by a pulse from the channel of any BUST counter. The counting rate of such a trigger is 17 s^{-1}.

The “Andyrchy” EAS array is located on the slope of the Andyrchy Mountain above the BUST and consists of 37 scintillation counters based on plastic scintillators [4]. A plastic scintillator with an area of 1 m^2 is viewed by a FEU-49B photomultiplier. Scintillation counters are designed for both temporal measurements (to determine the direction of an EAS arrival) and for measuring the energy release (to determine the position of the axis and the total number of particles in the EAS). The EAS trigger operates at a simultaneous triggering of four or more counters of the setup, the frequency of the trigger is ~9 s^{-1}. The distance between counters in the horizontal plane is 40 m. The central counter of an array is located directly above the BUST, the vertical distance is ≈350 m. Total area of the “Andyrchy” EAS array is 5×10^4 m^2 and the solid angle visible from the telescope is 0.35 steradian. The center of the setup is at an altitude of 2057 m above sea level, the height difference between the upper and lower rows of scintillation counters is 150 m.

The “Carpet-2” EAS array [6] is located at the foot of Andyrchy Mountain at a distance of 900 m from BUST, at an altitude of 1700 m above sea level (which corresponds to a depth in the atmosphere of 840 g /cm^2). The central part of the setup (the “Carpet” itself [5]) is located in a building under a roof of 29 g/cm^2 thickness and consists of 400 liquid scintillation counters (of the same type as the BUST), arranged in a square with a side of 14 m and covering an overall area of 196 m^2. Around the “Carpet-2” there are six remote points (RP) with a thin roof (~1.2 g/cm^2), in each of them there are 18 identical counters. Signals from a RP are used to determine direction of the EAS arrival.

The building of the muon detector (MD) consists of three tunnels with an area of 205 m^2 each. The thickness of the absorber is 500 g/cm^2, which corresponds to the threshold energy of muons of 1 GeV for the vertical direction. The distance between the centers of “Carpet” and MD is 47 m. Since 1999, the first MD stage of 175 m^2 area has been put into operation, consisting of 175 scintillation counters located in the central tunnel, of the type identical to that of the “Andyrchy” EAS array.

At present the “Carpet-3” EAS array is designed on base of the “Carpet-2” array [7]. Within the framework of creation of new apparatus, two tunnels were completely filled with scintillation counters and the total area of MD was brought up to 410 m^2. Realization of the EAS array suggests that continuous area of MD should be then increased up to 615m^2. At the same time, to increase the detection area of the EAS axes, 20 additional modules with liquid scintillation counters in each module will be installed. The results of calculations of selection efficiency of air showers from primary gamma rays demonstrated that the new array will have the world-best sensitivity to the flux of cosmic gamma rays with energies in the range 100 TeV – 1 PeV.

3. Multi-messenger astronomy at BNO: independent measurements of different messengers

An impressive example of the first type of multi-messenger observations is the measurement of fluxes of astrophysical gamma-rays and neutrinos. There is a connection between these fluxes because energetic photons accompany energetic neutrinos. The general model for production of energetic astrophysical neutrinos implies their creation in decays of charged pi-mesons (pions), produced in turn in high-energy hadronic or photohadronic interactions. These charged pions are necessary accompanied by neutral pions which decay to photons. Since the neutrinos propagate freely through the Universe while the photons may be absorbed, a comparison of the two fluxes may give important information about the distribution of sources.

The diffuse flux of astrophysical neutrinos has been measured in the IceCube experiment [8]. If such neutrinos are a result of decays of charge pions in the Galaxy halo the corresponding diffuse flux of primary gamma rays with energies higher than 100 TeV is close to experimental limits in this energy range [9]. Future searches for the diffuse gamma-ray background in this energy range just below current upper limits will give a crucial diagnostic tool for distinguishing between the Galactic and extragalactic models of origin of the IceCube events. The “Carpet-3” EAS array which is under development now will have the world-best sensitivity to the flux of cosmic gamma rays with energies in the range 100 TeV – 1 PeV [7]. So the measurement of diffuse flux of cosmic gamma rays in the “Carpet-3” experiment gives a principal possibility to resolve the problem of origin of astrophysical neutrinos detected in the IceCube experiment.

The search for primary photons with energies > 1 PeV, directionally associated with the IceCube high-energy neutrino events, has been performed using data obtained in 3080 days of Carpet-2 live time [10]. The first ever limits on PeV photons coming from the arrival directions of IceCube high-energy neutrino events were obtained. These limits may be used to constrain potential models of the neutrino origin in Galactic point sources. Besides, if the extragalactic origin of neutrinos is independently assumed, these results could constrain new-physics models affecting gamma-ray propagation.

4. Multi-messenger astronomy at BNO: synchronous observations.

For synchronous observations of astrophysical objects by means of different messengers it is necessary that these objects were simultaneously located in the field of view of different experimental facilities. Because the experimental facilities of the BNO must be operating all time the first requirement – simultaneity – is always automatically realized.

As the BUST cannot identify the arrival direction of low energy electron neutrinos/antineutrinos, the whole sky is accessible for us in the searching of these particles. First of all, it is necessary to note the search for neutrino bursts from supernovae at the BUST [11]. In this experiment the best limit on the mean frequency of collapses in the Galaxy has been obtained.

For the reason of the background suppression, for the search of electron neutrino/antineutrino in the energy range from 21 MeV to 100 MeV the reactions of their interaction with carbon in a scintillator are used [12, 13]. This technique was used at the BUST for the search of neutrino signal in time coincidence with cosmic gamma-ray bursts (GRBs) and gravitational wave events. So, no neutrino signals associated with 97 gamma-ray bursts recorded during 2012 by SWIFT in the time window ±1000 s were found [12]. Also no neutrino signals in the interval of ±500 s from the gravitational wave events GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817 have been detected. Only limits on the fluxes of low-energy electron neutrinos and antineutrinos from astrophysical sources of gravitational bursts have been obtained [13]. Figures 1 and 2 show the upper limits (at 90% C.L.) obtained at the BUST on the fluxes of electron neutrinos and antineutrinos from gravitational wave events as functions of their energy (for a monoenergetic spectrum) in comparison with the Borexino, KamLAND, and Super-Kamiokande results.

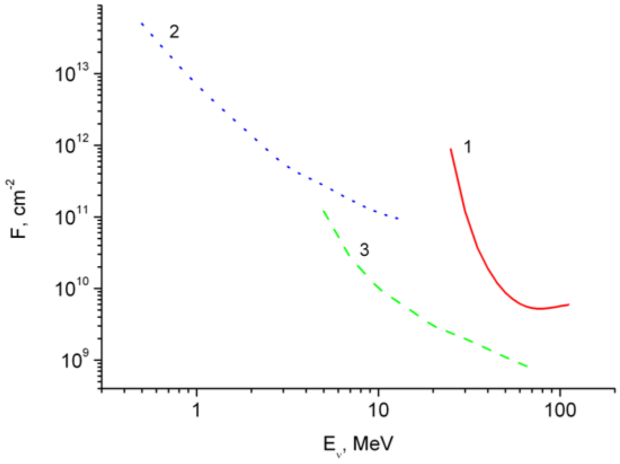

Fig1. Upper limits on the flux of electron neutrinos versus their energy (for a monoenergetic spectrum) according to (1) reaction with carbon at the BUST, (2) elastic scattering at the Borexino detector, and (3) elastic scattering at the Super-Kamiokande detector.

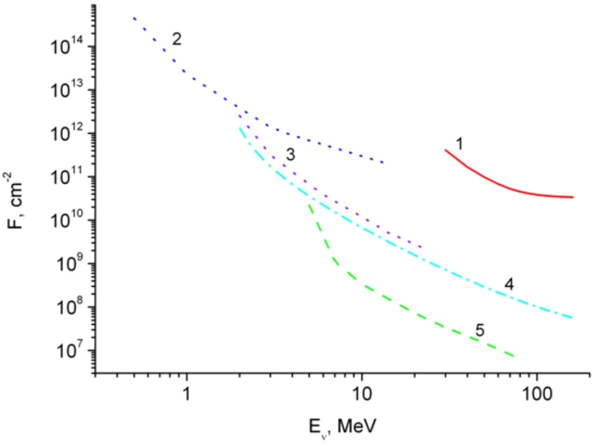

Fig2. Upper limits on the flux of electron antineutrinos versus their energy (for a monoenergetic spectrum) according to (1) reaction with carbon at the BUST, (2) elastic scattering at the Borexino detector, (3) inverse beta decay at the Borexino detector, (4) inverse beta decay at the KamLAND detector, and (5) inverse beta decay at the Super-Kamiokande detector.

The BUST construction allows us to identify tracks of muons crossing the telescope. Muons from the lower hemisphere can be only from muon neutrinos whose traveling through the rock may interact with nucleons to create energetic muons. Separation of arrival directions between the upper and lower hemispheres is carried out using the time-of-flight method. Hence we can perform the search of muon neutrinos from astrophysical objects only for objects located in the lower hemisphere at the moment. Selection criteria of neutrino events in the BUST cut off particles with energies below 1 GeV.

The search for muon neutrinos with energy ≥1 GeV correlated with GRBs has been carried out at the BUST [14]. Between December 1978 and December 2013 more than 1500 localized GRBs, which occurred in the field of view of the BUST, coincided with the BUST operation periods. No neutrino signal from GRBs was detected. Figure 3 shows the model-independent GRB neutrino upper limits on GRB neutrino fluence per GRB obtained at the BUST in comparison with results of other experiments.

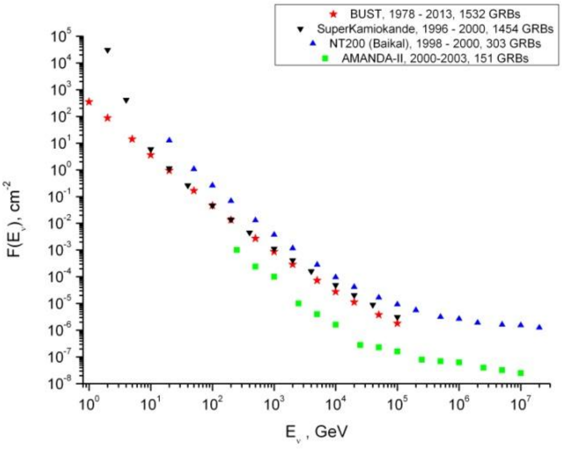

Fig3. *The 90% CL upper limits versus their energy (for a monoenergetic spectrum) on GRB neutrino fluence per GRB obtained at the BUST, Super-Kamiokande, AMANDA and Baikal.*

5. Multi-messenger astronomy at BNO: fast response astronomy

The search for optical partners of bursts of cosmic gamma-ray radiation and cosmic ray intensity of high and very high energy range is conducted using the experimental facilities of the BNO and a complex of astronomical telescopes at Peak Terskol Observatory of the Institute of Astronomy of RAS. The bursts of cosmic ray intensity and cosmic gamma radiation are detected at the BNO experimental facilities. The search and subsequent study of optical flares associated with the detected BNO events are carried out on a complex of astronomical telescopes at the peak Terskol. This experiment is aimed at obtaining new experimental data on astrophysical objects generating bursts of cosmic gamma radiation of high energy together with optical flashes. Such bursts of radiation can be generated by processes in the nuclei of galaxies, by interaction of astrophysical objects, at the last stage of evolution of stars including supernova bursts. Now the search for bursts of cosmic ray intensity and cosmic gamma radiation is carried out by means of method of a search for spatiotemporal concentrations (clusters) of showers recorded by the EAS array. Previously this method was used to search at experimental facilities of BNO for high energy gamma-radiation from cosmic gamma-ray bursts (CGRB) and from evaporating primordial black holes (PBH) [15 – 18]. At present the search for bursts of cosmic ray intensity and cosmic gamma radiation by means of detection of clusters of showers is realized in the near-real-time mode. Because the experimentally measured frequencies of cluster registration of different multiplicity are in agreement with the frequencies expected from the background fluctuations of cosmic rays the new method of background suppression was developed [19]. This method of background suppression allows us using selected clusters of showers as alerts to search for transient phenomena in the optical range.

The search for optical counterparts of the high energy ($E_\nu \geq 1$ GeV) muon neutrinos is carried out now in the near-real-time mode using the neutrino alerts from BUST. The follow up optical observations is conducted at the robotic telescopes of the Global MASTER Robotic Net [20].

6. Conclusion

The multi-messenger astronomy is now in the stage of rapid growth. This growth is provided both by a large number and variety of telescopes conducting the joint search in a wide range of electromagnetic radiation (from radio to gamma) and by participating in joint projects of installations recording gravitational waves and ultrahigh-energy neutrinos. The development of modern experimental facilities and fast data acquisition systems (DAQ) gives a possibility to analyze experimental data in real-time mode. Such methodical approach gives, in turn, a possibility to study of the dynamics of explosive processes in the detected transient objects. At present the fundamental modernization of data acquisition systems of experimental facilities of BNO is performed [21]. This modernization will make it possible to produce the low-latency alerts from experimental facilities of BNO for various nets of robotic telescopes.

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