Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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IOP Conf. Series: Journal of Physics: Conf. Series 1181 (2019) 012058 doi:10.1088/1742-6596/1181/1/012058

Search for electron neutrinos associated with gravitational-wave events at the Baksan Underground Scintillation Telescope

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Abstract. Results of a search for electron neutrinos from the gravitational wave events GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817 at the Baksan underground scintillation telescope (BUST) are presented. We searched for coincident neutrino candidates in the data recorded by the BUST detector. No neutrino candidates in temporal coincidence with the gravitational wave events were found. Upper bounds on neutrino and antineutrino fluence from astrophysical sources of gravitational bursts have been set.

1. Introduction

Astronomers with LIGO and its collaborating detector Virgo have registered six gravitational wave events from the merger of neutron stars and black holes: GW150914 [1], GW151226 [2], GW170104 [3], GW170608 [4], GW170814 [5], and GW170817 [6]. These events can result in a black hole plus accretion disk system that produces non-thermal, high-energy radiation and may have a neutrino component. The observation of gravitational wave sources with multiple cosmic messengers is a unique opportunity that enables the detailed study of the phenomena. The detection of gravitational wave events initiated the search for their astrophysical sources. No reliable signals have been detected from the first five gravitational wave bursts. On August 17, 2017, the Advanced LIGO and Advanced Virgo observatories recorded a GW signal, GW170817. Soon afterwards, Fermi-GBM and INTEGRAL detected a short GRB from a consistent location [7]. Subsequently, ultraviolet, optical, and infrared emission was observed from the merger. Optical observations allowed the precise localization of the merger. Neutrino observatories continuously monitor the whole sky making them well suited to study emission from GW sources.

Astrophysicists searched for high-energy neutrinos from the gravitational wave events in the energy band of [10^{11}eV, 10^{20} eV] using the ANTARES, IceCube, and Pierre Auger Observatories, as well as for MeV neutrinos with IceCube. Also, scientists searched for possible neutrino signals coincident with gravitational wave events in Borexino [8], Super-Kamiokande [9, 10] and KamLAND [11] experiments using a wide energy range from 3.5 MeV to 100 PeV [12, 13, 14, 15, 16, 8, 11, 9, 10]. In all experiments, neutrino events were sought in a time interval of $\pm$500 s, as the maximum time interval between a neutrino signal and corresponding gravitational wave event [17]. Neutrino signals from gravitational wave events were not detected in any of the listed experiments. The number of neutrino candidate events observed in the search window can be converted to an upper limit on neutrino fluence for all of the gravitational wave events. This is done for all listed above neutrino experiments.

Electron antineutrinos were sought at the Borexino, Super-Kamiokande and KamLAND experiments through the inverse beta decay (IBD) reaction

$$\overline{\nu_e} + p \to n + e^+, \tag{1}$$

which has a low threshold $E_{e^+} = E_{\overline{\nu_e}} - 1.3$ MeV and the largest cross section in the range from 0.5 to 110 MeV. The search at the Borexino and Super-Kamiokande experiments was also performed for elastic scattering (ES)

$$\nu + e^- \to \nu + e^-, \tag{2}$$

which is sensitive to all types of neutrinos and has the largest cross-section for electron neutrinos.

Because of the background conditions at the BUST, to seek low-energy electron neutrinos and antineutrinos from gravitational wave events, the reactions of their interaction with carbon in a scintillator were used. In this work, we report upper limits obtained at the BUST on fluxes of electron neutrinos and antineutrinos with energies above 21 MeV from astrophysical sources of the GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817 gravitational bursts.

2. Baksan underground scintillation telescope

The Baksan underground scintillation telescope (BUST) is a multipurpose detector designed for a wide range of investigations in the physics of cosmic rays, elementary particles, and neutrino astrophysics. The telescope is located in the Northern Caucasus (Russia) in an underground laboratory at an effective depth of 850 m.w.e.[18, 19]). BUST is one of the largest underground detectors operating at the Baksan Neutrino Observatory of the Institute for Nuclear Research. The detector is a $17 \times 17 \times 11$ m parallelepiped with modular structure and two additional internal planes. The planes are covered by standard scintillator counters. The total number of counters in the BUST is 3184. The total mass of the scintillator is 330 t.

A standard scintillator counter is a $0.7 \times 0.7 \times 0.3$ m aluminium tank filled with liquid organic scintillator based on white spirit $C_nH_{2n} + 2 (n \simeq 9)$. The scintillator volume is viewed by one FEU-49 photomultiplier tube with a photocathode diameter of 15 cm. The most probable energy deposition in a counter from muons is 50 MeV. Four signals are recorded from each counter. A signal from the anode of the photomultiplier tube is used to measure the plane trigger time and the energy deposition up to 2.5 GeV.

The current output (the signal from the anode of the photomultiplier tube through an integrating circuit) is used to adjust and control the gain of the photomultiplier tube. The signal from the 12th dynode is fed to the input of a discriminator (the so-called pulse channel) with a trigger threshold of 8 and 10 MeV for the horizontal and vertical planes, respectively. The signal from the fifth dynode of the photomultiplier tube is fed to the input of a logarithmic converter, where it is converted into a pulse whose length is proportional to the logarithm of the signal amplitude. The logarithmic channel allows the energy deposition in an individual counter to be measured in the range of 0.5 - 600 GeV.

The triggering of the pulse channel for any BUST counter is used as a trigger for the recording system. The trigger count rate is 17 s^{-1}. When a trigger appears, the entire information on this event is fed to an online computer, where the events are preprocessed in order to obtain information on the current status of the detection instrument. The GPS signal is used for synchronization with Universal Time with an accuracy of 0.2 ms.

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3. Search methods

One of the important tasks performed by the BUST experiment, we should mention the detection of the neutrino burst from the collapse of the core of an exploded supernova. This was detected using the signals from three bottom horizontal planes comprising 1200 counters and containing 130 t of the scintillator.

The neutrinos are detected through the reaction of inverse beta-decay. Given that the mean energy of Supernova antineutrinos is $E_{\nu_e} \simeq 12 - 15$ MeV, the path of the positron produced in reaction (1) is comparable with the size of one detector module. The detector response to such an event referred to as the single firing, is the isolated pulse from a single counter. The supernova collapse is detected as a series of single-counter firings throughout the neutrino burst. The active shield is provided by the detectors external planes operating in anticoincidence mode. Three lower inner horizontal planes containing 1200 counters with 130 t of scintillator are used as targets. The count rate in these planes from background events is 0.02 s^{-1}. Because of such a count rate of background events, the inverse beta decay reaction cannot be used to seek neutrino events from gravitational bursts because a much wider time window of 1000 s is involved and the number of background events becomes unacceptably large.

For this reason, low-energy electron neutrinos (antineutrinos) from gravitational bursts are sought at the BUST through the reactions of their interaction with carbon in a scintillator:

$$\nu_e +^{12} C \rightarrow^{12} N + e^-, \tag{3}$$

$$\overline{\nu_e} +^{12} C \rightarrow^{12} B + e^+. \tag{4}$$

Events of production of unstable ^{12}N and ^{12}B isotopes (with the lifetimes $\tau(^{12}N) = 15.9$ ms and $\tau(^{12}B) = 29.1$ ms) in reactions (3) and (4) and their subsequent decay involve two successive counts of the same counter. The main (and quite well-studied) source of the background for the detection of low-energy electron neutrinos/antineutrinos is the interaction of neutrons with carbon nuclei $n +^{12} C \rightarrow^{12} B + e^+$ in the scintillator of the counters of the BUST with the production of the unstable ^{12}B isotope [20]. Thus, successive single counts of the same counter in the range of 150 ms ($> 5 \cdot \tau(^{12}B)$) are considered as candidates for low-energy neutrino events from gravitational bursts at the BUST. The selection of such events makes it possible to significantly reduce the background and, as a result, to increase the mass of the target scintillator to 240 t by adding 1020 counters of the outer planes of the BUST to 1200 counters of the inner planes.

No events that could be interpreted as signals from the interaction of electron neutrinos/antineutrinos with carbon nuclei of the target were detected at the BUST within the interval of ±500 s from the GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817 gravitational wave bursts. Furthermore, the minimum interval between a possible neutrino signal at the BUST and the GW151225 gravitational wave event is about 1 d. According to the absence of neutrino signals, we obtained the upper limits (90% C.L.) on the flux of electron neutrinos and antineutrinos with different energies under the assumption of a monoenergetic spectrum:

$$F(E_\nu) = \frac{n_{90}}{S(E_\nu)}, \tag{5}$$

where $n_{90} = 2.3$ and $S(E_\nu)$ is the effective area of detection of the electron neutrino/antineutrino, which can be represented in the form

$$S(E_\nu) = \epsilon \cdot N \cdot \sigma(E_\nu) \cdot [\delta_{in} \cdot P_{in}(E_\nu) + \delta_{out} \cdot P_{out}(E_\nu)] \tag{6}$$

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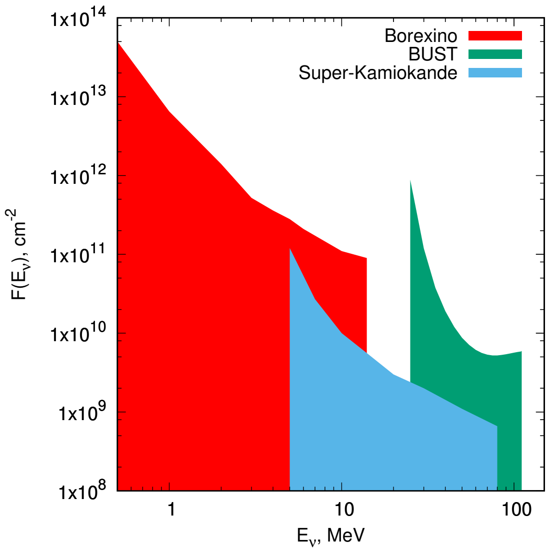

Figure 1. Upper limits (at 90% C. L.) on the electron neutrino flux from gravitational wave source during a ±500 s window centered on the gravitational wave trigger time.

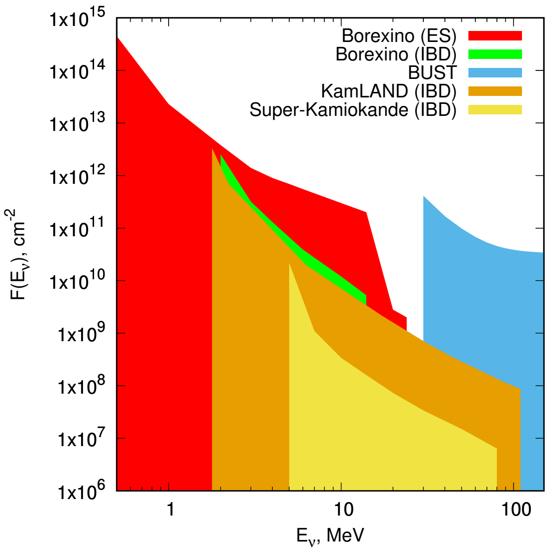

Figure 2. Upper limits (at 90% C. L.) on the electron antineutrino flux from gravitational wave source during a ±500 s window centered on the gravitational wave trigger time.

Here, $\sigma(E_\nu)$ is the cross section for the interaction of the electron neutrino/antineutrino with the carbon nucleus (reactions (3) and (4), [21, 22]), $N = 10^{31}$ is the total number of carbon atoms in the target, $\epsilon = 0.94$ is the fraction of the pure detection time during the search for neutrino signals from gravitational wave events, and δ_{in} and δ_{out} are the fractions of the target mass in the inner and outer planes of the BUST, respectively. The efficiencies of detection of events from the interaction of electron neutrinos/antineutrinos with carbon nuclei in scintillator are different for the inner ($P_{in}(E_\nu)$) and outer ($P_{out}(E_\nu)$) planes of the BUST because of different triggering thresholds of the counters of the inner (8 MeV) and outer (10 MeV) planes of the telescope. These efficiencies for reactions (3) and (4) were calculated taking into account the efficiency of detection of electrons/positrons in the counters of the BUST [23] and beta spectra of ^{12}B and ^{12}N[24].

4. Conclusion and results

We search for possible neutrino signals coincident with GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817 in the BUST detector using an energy range from 21 MeV to 200 MeV. No neutrino candidate events are found in the search window of ±500 s around the LIGO detection time for all gravitational wave signals.

Figures 1 and 2 show the upper bounds (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. To detect electron neutrinos at the Borexino and Super - Kamiokande facilities, elastic scattering of neutrinos on electrons (2) was used. To detect electron antineutrinos at the Borexino facility, elastic scattering (at lower energies) and inverse beta decay (1) were used. Inverse beta decay was used to seek electron antineutrinos from gravitational wave events at the KamLAND and Super-Kamiokande facilities.

Upper limits obtained in our experiment are identical for all GW150914, GW151226, GW170104, GW170608, GW170814, and GW170817 gravitational wave events. The Borexino bounds shown in the figures are the average for three events GW150914, GW151226, and GW170104 [8]. Electron antineutrinos were sought at the KamLAND facility for the GW150914 and GW151226 events and the bound for the GW150914 event is shown in figure 2 as more stringent [11]. Bounds on the fluxes of electron neutrinos and antineutrinos were obtained at the Super-Kamiokande facility for the GW150914, GW151226, and GW170817 gravitational wave events and the most stringent bounds are also shown in figures 1 and 2 [9, 10].

Acknowledgments
The work has been carried out at a unique scientific facility the Baksan Underground Scintillation Telescope (Common-Use Center Baksan Neutrino Observatory INR RAS) and was supported by the Program for Fundamental Scientific Research of RAS Presidium "Fundamental Interactions Physics and Nuclear Technologies".

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