Search for muon neutrinos from the gravitational wave event GW170817 at the Baksan Underground Scintillation Telescope

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Abstract. Using data of the Baksan Underground Scintillation Telescope we have searched for muon neutrinos and antineutrinos with energies above 1 GeV coinciding with the gravitational wave event GW170817 that was recorded on August 17, 2017, by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and Advanced Virgo observatories. This is the first detection of the new type of events occurring as a result of a merger of two neutron stars in a binary system. A short gamma-ray burst (GRB) GRB170817A accompanying this event is evidence of particle acceleration in the source whose precise position was determined by detection of the subsequent optical signal. No neutrino signals were found with the Baksan Underground Scintillation Telescope in the interval ±500 s around the moment of the gravitational wave event GW170817, as well as during the next 14 days. The upper limits on integral fluxes of muon neutrino and antineutrino from the source are derived.

1. Introduction

The gravitational wave (GW) event GW170817 [1], which was detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and Advanced Virgo observatories, was interpreted as a result of merging neutron stars in a binary system. Identification of this event with the gamma-ray burst (GRB) event GRB170817A that was detected by Fermi Gamma-ray Burst Monitor (Fermi GBM) in 1.7 s after the merger has confirmed the hypothesis about merging neutron stars and produced a direct proof of connection between merging neutron stars and short gamma-ray bursts. Subsequent detection of afterglow of the source in a wide range of wavelengths of electromagnetic radiation has confirmed the interpretation of this event as neutron star merging [2].

The search for high-energy neutrinos from the GW170817 event was done by the neutrino telescopes ANTARES (the name comes from Astronomy with a Neutrino Telescope and Abyss environmental RESearch project), IceCube (IceCube Neutrino Observatory) and Baikal Gigaton Volume Detector (Baikal-GVD), as well as by the air shower array of the Pierre Auger Observatory (named after the French physicist Pierre Victor Auger) and Super-Kamiokande...
Figure 1. Scheme of the arrangement of the counters in BUST.

(abbreviation of Super-Kamioka Neutrino Detection Experiment) underground detector [3–5]. All these experiments used two time intervals when searching for neutrino events. The first one, ±500 s relative to the merger moment (the maximum possible interval between a gravitational wave and neutrinos from cosmic gamma ray bursts), was used in [6, 7] in order to search for prompt and prolonged gamma ray emission. The second interval, lasting 14 days after the merger, was used to search for high energy neutrinos from a long-living magnetar produced by merging neutron stars of a binary system [8, 9].

None of the above listed experiments has found a signal from the GW1709817 gravitational event. The upper limits on the integral fluxes of neutrinos and on the total energy of neutrinos emitted by the source were obtained. We report the results of a search for high energy muon neutrinos in the Baksan Underground Scintillation Telescope (BUST) associated with GW170817. We searched for coincident events in the experimental data sample using the same time window as mentioned neutrino telescopes, i.e., ±500 s around the merger time and in a 14-day time window following after GW event.

2. Baksan Underground Scintillation Telescope
The BUST detector is located in Baksan Valley (North Caucasus, Russia) within an underground laboratory at an effective depth of 850 m of water equivalent. It is a multi-purpose instrument designed for a wide range of studies into physics of cosmic rays and elementary particles, and neutrino astrophysics [10,11]. The telescope of dimensions $17 \times 17 \times 11 \text{ m}^3$ consists of 4 horizontal and 4 vertical planes with scintillation counters, the total number of which in the BUST being equal to 3184 (figure 1). The standard scintillation counter is an aluminum container with dimensions $0.7 \times 0.7 \times 0.3 \text{ m}^3$ filled with organic liquid scintillator using white spirit as a solvent $C_nH_{2n+2}$ ($n \approx 9$).

Each scintillation counter (figure 2) is viewed by a single photomultiplier tube (PMT) “FEU-49B” with a photocathode diameter of 15 cm. The most probable energy release of muons in the counter is 50 MeV. Each counter has four output signals. The PMT anode signal is used
Figure 2. Scintillation counter layout.

for fixing the time of a plane triggering and for measuring its energy release up to 2.5 GeV. The current output (anode signal coming through an integrating circuit) is used for adjustment and control of PMT gains. Signals from the twelfth dynodes feed the inputs of pulse shape discriminators (the so-called pulse channel) with threshold amplitudes 8 and 10 MeV for the inner and outer planes respectively. The signal from the fifth dynode comes to the input of a logarithmic converter, where it is transformed into a pulse whose duration is proportional to the logarithm of signal amplitude. The logarithmic channel allows one to measure the energy release in each counter within the energy range 0.5–600 GeV.

The data acquisition system is triggered by the actuation of the pulse channel of any BUST counter. The count rate of such a trigger is $17 \, \text{s}^{-1}$. When a trigger appears all data about a given event come to the on-line computer where pre-processing of events is performed to get information about the current state of recording devices. Global positioning system (GPS) signals with a synchronization accuracy of 0.2 ms are used to reference events with the universal time.

3. Experiment

The BUST design allows one to identify trajectories of the muons crossing the telescope and to determine the muon arrival direction. The angular resolution of the instrument is $\approx 1.6^\circ$. It should be noted that the arrival direction of a muon produced in a neutrino reaction with matter strongly correlates with the neutrino arrival direction. The root mean square angle between a muon and its parent neutrino equals $\approx 3.7^\circ$ for the energy spectrum of atmospheric neutrinos. Since the calculated spectra of neutrinos from astrophysical sources are harder than those of atmospheric neutrinos, one could expect a smaller angular distance between arrival directions of recorded muons and the direction to an astrophysical object.

When detecting muons from the lower hemisphere ($\theta > 90^\circ$) one can exclude the background from muons penetrating underground (since all known components of cosmic rays are absorbed at a depth of several kilometers of rock), if the flux of back-scattered muons from above is less
than the neutrino effect at the telescope depth. For the BUST depth, the muon background is totally excluded when zenith angles are $\theta > 100^\circ$. When an object is located in the upper hemisphere one can also search for muon neutrinos in the given time interval, provided that the muon background for a given direction is small, i.e., for directions with a sufficiently large thickness of matter.

Separation of arrival directions of muons between the upper and lower hemispheres is realized using the time-of-flight method. The time resolution of the telescope, when the relative time of flight between two scintillation planes is measured, equals 3.5 ns, and it is mainly determined by counter properties. For single muons from the upper hemisphere the reconstructed value of inverse velocity $1/\beta$ ($\beta = v/c$) lies within the range 0.7–1.3 for 95% of events [12]. The same interval, but with the negative velocity sign is used to select muons from the lower hemisphere, generated in neutrino interactions with matter (rock) below the telescope. The threshold energy of muon neutrinos detected by the BUST is determined by energy losses of muons crossing the telescope, and it is equal to 1 GeV for the used selection criteria.

4. Search for muon neutrinos from GW170817

Figure 3 presents the location of the GW170817 event in the local coordinate system $(Az, H)$, where $H$ is the elevation angle above the horizon, and $Az$ is the azimuth angle reckoned from the south direction. Also shown is the source trajectory during the first day after recording the gravitational wave event.

During nine hours per day, the source is located above the horizon, the minimum thickness of matter for these directions being equal to $\sim 10^6$ g/cm$^2$ [13]. This thickness of rock at the place of telescope location corresponds to the path length of muons with energy $\sim 10^5$ GeV [14]. Muon neutrinos from GW170817 were searched for in a circle with a radius of 5°. In a time interval $\pm 500$ s around the merging moment not a single event was found, in accordance with the expected number of background events from cosmic ray muons.

![Figure 3. The GW170817 event location (asterisk) and its trajectory in the local coordinate system $(Az, H)$ during the first day after detection.]
Figure 4. Upper limits on integral fluxes of muon neutrinos and antineutrinos from GW170817 for the time interval ±500 s as functions of their energy (for mono-energetic spectrum).

During 14 days following after GW170817 three muon events were detected, which is also in agreement with the expected number of background events (equal to 2.6) produced by cosmic ray muons. All these events came from the upper hemisphere at elevation angles ranging from 6° to 23°.

5. Neutrino fluence limit

From the fact of absence of neutrino signals from the source the upper limits (90% confidence level) on integral fluxes of muon neutrinos and antineutrinos were derived as functions of their energy assuming monoenergetic spectrum (figure 4):

\[ F(E_\nu) = \frac{N_{90}}{\varepsilon S(E_\nu)}, \]

where \( E_{\text{min}} = 1 \text{ GeV}, E_{\text{max}} = 10^5 \text{ GeV}, S(E_\nu) \) is the effective area of detection of muon neutrino (or antineutrino) with energy \( E_\nu \), \( N_{90} \) is the 90% confidence level limit calculated from a Poisson distribution for the observed neutrino events with the expected background, and \( \varepsilon = 0.84 \) is the portion of neutrino events from a point-like source within a circle of radius 5°. Since there is no neutrino events found \( N_{90} \) can be fixed of \( N_{90} = 2.3 \).

The limits are derived separately for muon neutrino and antineutrino, because interaction cross-sections are different for muon neutrinos and antineutrinos [15], so that their effective areas of detection are different too. Under assumption of the power-law spectrum with exponent \(-2\), the upper limits on integral fluxes of muon neutrinos and antineutrinos from GW170817 are obtained for the energy range from \( E_{\text{min}} = 1 \text{ GeV} \) to \( E_{\text{max}} = 10^5 \text{ GeV} \) (with \( I(E_\nu) = E_\nu^{-2} \)):

\[ F_\nu = \frac{N_{90}}{\varepsilon \int_{E_{\text{min}}}^{E_{\text{max}}} dE_\nu S(E_\nu) I(E_\nu)}. \]
In the energy range specified above the upper limits with 90% confidence level are equal to $57.3\ \text{cm}^{-2}$ and $113.0\ \text{cm}^{-2}$ for muon neutrino and antineutrino, respectively. Figure 5 presents the upper limits on the energy fluxes in muon neutrino and antineutrino from GW170817 for the time interval $\pm500\ \text{s}$. The limits are calculated separately for every decade of energy and under assumption of a power-law energy spectrum with index of $-2$:

$$\Phi_{\text{lim}} = \frac{N_{90}}{E_2 - E_1} \int_{E_1}^{E_2} dE_\nu E_\nu I(E_\nu) \frac{\varepsilon}{E_2 - E_1} \int_{E_1}^{E_2} dE_\nu S(E_\nu) I(E_\nu).$$

(3)

6. Conclusion
We made a coincidence search for neutrino signals with the GW event GW170817 in the BUST detector in an energy range from $1$ to $10^5\ \text{GeV}$. The analysis was performed within a time window of $\pm500\ \text{s}$ of GW170817 and 14 days after the GW event. No muon neutrino event was found in the $\pm500\ \text{s}$ window in accordance with the expected number of background events from cosmic ray muons. The number of neutrino events in a 14-day time window is consistent with the estimated background rate. Considering the observation no neutrino signal associated with the GW170817 in BUST detector, we calculated the neutrino and antineutrino fluence limits (figure 5). The obtained results are in a good agreement with the results of other observatories.

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