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SEARCH FOR LOW-ENERGY NEUTRINOS FROM GAMMA-RAY BURSTS AT THE BAKSAN UNDERGROUND SCINTILLATION TELESCOPE

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The origin of gamma-ray bursts is still one of the unresolved problems in physics. They are short, intense, and nonrepeating flashes of MeV gamma rays with a wide range of spectral and temporal properties. Also, these bursts are perhaps the sources of neutrino emission. Unlike the photons, which may scatter or be absorbed, the neutrinos, due to their small interaction cross section, arrive at the Earth unaffected. This paper describes experimental methods for detection of low-energy neutrinos in the range from 20 to 100 MeV at the Baksan Underground Scintillation Telescope (BUST). In the analysis, we search neutrinos in time coincidence with a gamma-ray burst. We use filtered data collected at the Telescope during 2012. We also use the catalogue of gamma-ray bursts of the SWIFT satellite experiment.

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INTRODUCTION

Gamma-Ray Bursts (GRBs) are one of the most fascinating research topics in astrophysics. They are flashes of gamma rays associated with extremely energetic explosions at cosmological distances, the equivalent isotropic energy released can be as high as 10^{51}–10^{54} erg. GRBs display a bimodal duration distribution, with a separation between the short- and long-duration bursts at about 2 s. The origin of GRB and the processes taking place during the burst that give rise to the observed radiation are poorly understood. GRBs perhaps emit neutrinos [1].

Models describing the gamma-ray bursts are partly based on the observations of the so-called afterglow, which can last for a much longer period. The prevalent belief is that the progenitors of long GRBs, which have a duration greater than two

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seconds, are very massive stars that undergo core collapse by formation of a black hole (the collapsar [2] and supernova [3] models). Short GRBs are believed to be the product of the merger of binary compact objects such as neutron stars [4]. The central engine of GRB can collimate relativistic jets that propagate inside the stellar envelope. Material is ejected from the progenitor in ultrarelativistic jets, which then produce the observed burst of gamma rays. In GRB (whether from compact mergers or from collapsar scenarios), the central material is compressed to nuclear densities and heated to virial temperatures characteristically in the multi-MeV range, leading to 5–30 MeV thermal neutrinos. A short pulse of electron neutrinos, ν_e, produced via core collapsing is emitted immediately before the main pulse. In this scenario, the neutrino emission is associated with the cooling phase of the collapsed object. The same mechanism occurs in a supernova, when the core collapses to the form of a protoneutron star and emits neutrinos in the same energy region. The neutrino and gamma signals are separated by time interval depending on the time necessary to transfer energy from the central engine of GRB, which emits neutrinos, to the outer region ejecting high-energy photons. The detection of these neutrinos would give more insight into the origin of GRB phenomena. In this article, we describe the search for such neutrinos at the Baksan Underground Scintillation Telescope (BUST) in coincidence with the SWIFT satellite observations of GRBs during 2012 [5].

1. THE BUST OVERVIEW

The Baksan Underground Scintillation Telescope was created for investigation of cosmic-ray muons and neutrinos. The facility is located in an excavation under the slope of Mt. Andyrchy (North Caucasus, 43.28°N and 42.69°E) at the effective rock depth 850 hg/cm^2 (300 m of a rocky ground), which corresponds to the threshold energy of detected muons of about 220 GeV.

The BUST represents a parallelepiped with the height of 11 m and basis of 17×17 m. Its floor as well as walls are fully covered with scintillation detectors, which form 8 planes (4 vertical and 4 horizontal, three of the latter being the internal ones, see Fig. 1). The distance between the neighboring horizontal planes is 3.6 m. The upper horizontal plane consists of 24×24 scintillation detectors, the rest three planes accommodate 20×20 detectors each. Three vertical planes have 15×24 detectors and one vertical plane is built of 15×22 detectors. The total mass of the liquid scintillator contained in these 3186 detectors $\simeq 330$ t. The inner planes of the BUST have the effective mass of $\simeq 130$ t and are used for detection of events in the low-energy region. The outer planes serve as an active shield.

A standard scintillation detector of the BUST is an aluminium container of $0.7 \times 0.7 \times 0.3$ m viewed by a 15-cm diameter photomultiplier (PMT) FEU-49B through a poly(methyl methacrylate) ($(C_5O_2H_8)_n$) illuminator (see Fig. 2). The detector is filled with the liquid-scintillator white spirit (C_9H_{20})

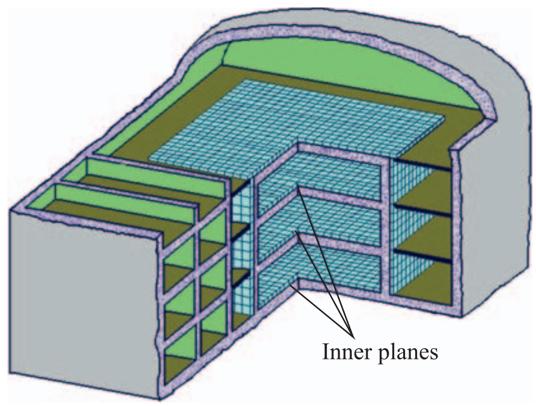

Fig. 1. The Baksan Underground Scintillation Telescope (BUST)

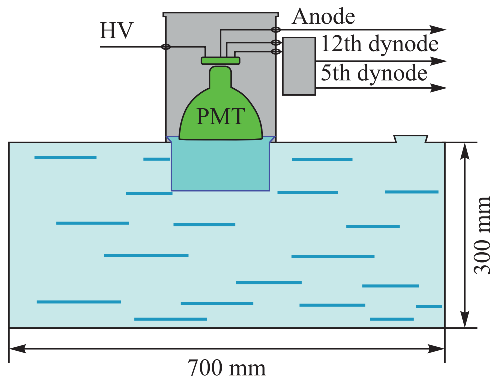

Fig. 2. A standard scintillation detector of the BUST

and the flour 2,5-diphenyloxazole ($C_{15}H_{11}NO$) as a solute at concentration of 1 g/l. The scintillator has also a small admixture (0.03 g/l) of 1,4-bis(5-phenyloxazol-2-yl) benzene ($C_{24}H_{16}N_2O_2$) as a wavelength shifter. The most probable energy deposition in a detector at passage of a near-vertical muon is about 50 MeV. The anode output of PMT serves for measurements of the energy deposit in the plane in the energy range from 7 MeV to 2.5 GeV. A pulse channel with an operating threshold of 10 MeV (8 MeV for the inner planes) is connected to the 12th dynode and provides the coordinate information. The signal from the 5th dynode of PMT is used to measure the energy deposit in the detector in the range from 0.5 to 600 GeV by means of the logarithmic converter of the pulse amplitude to duration. Since 2001, the BUST uses a new data-acquisition system recording all the events in which one or more detectors are fired.

2. NEUTRINO DETECTION

Neutrinos are detected via electromagnetically or strongly interacting products of the weak charged-current and neutral-current reactions with electrons and nuclei. The most probable interaction in the BUST scitillator is the inverse β decay $\bar{\nu}_e + p \to n + e^+$, which is the interaction between $\bar{\nu}_e$ and free protons with the neutrino energy threshold $E_{\rm thr} = 1.8$ MeV. The positron energy loss can typically be observed. Besides, the abundance of carbon in the organic liquid scintillator provides an additional target for neutrino interactions:

- charged-current reaction of $\bar{\nu}_e$:
  $\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$, $E_{\rm thr} \simeq 14.4$ MeV,
  ${}^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$, $\tau \simeq 29.1$ ms;
- neutral-current inelastic scattering of all three types of neutrinos:
  $\nu_l + {}^{12}\mathrm{C} \to {}^{12}\mathrm{C}^* + \nu_l$, $E_{\rm thr} \simeq 15.1$ MeV,
  ${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma$, $Q_\gamma \simeq 15.1$ MeV;
- charged-current reaction of ν_e:
  $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$, $E_{\rm thr} \simeq 17.3$ MeV,
  ${}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e$, $\tau \simeq 15.9$ ms.

In the case of the charged-current reactions, the signature is the charged particle (e^+ or e^-) emitted in the prompt reaction, followed tens of milliseconds later by the β decay (β^+ or β^-) back to ^{12}C. The delayed signal coincidence enables us to identify these specific interactions from background.

The module structure of the BUST allows us to separate single-hit events (where just one of the detectors fires) and multiple-hit events (where more than one detector fire).

The effective area of the BUST $S_{\rm eff}(E)$ for the described reactions is defined as

$$S_{\rm eff}(E) = n_c\, \epsilon\, \sigma(E)\, (1 - \mathrm{e}^{-\Delta t/\tau}), \tag{1}$$

where ϵ is the detection efficiency; n_c is the effective number of ^{12}C nuclei in the scintillator; $\sigma(E)$ is the neutrino interaction cross section; τ is the mean lifetime of the corresponding isotope; Δt is the time elapsed since this isotope was produced. The cross sections for the neutrino–carbon reactions have been investigated theoretically [6] and experimentally [7, 8] and are now well established. The neutrino effective area is the equivalent area for which all neutrinos impinging on the BUST would be observed. Figures 3 and 4 depict the BUST effective areas for the charged-current neutrino reactions on carbon as functions of the incident neutrino energy.

Note, that $S_{\rm eff}(E)$ increases due to the increase of the neutrino–carbon cross section with neutrino energy.

The BUST data collected in 2012 were used in our low-energy neutrino search analysis. The interactions producing pairs of single-hit signals were selected by applying the following criteria:

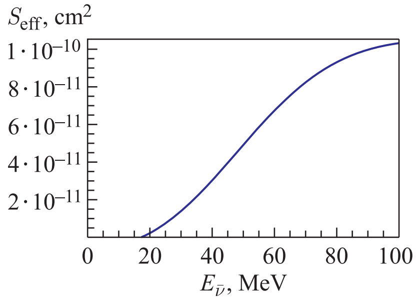

Fig. 3. Effective area of the BUST for the reaction $\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$

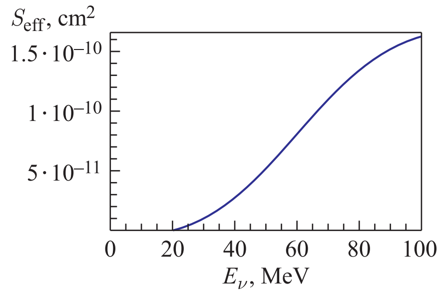

Fig. 4. Effective area of the BUST for the reaction $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$

• selected single-hit signals are separated by time interval $\Delta t \leqslant 150$ ms (5 lifetimes of ^{12}N) and belong to the same detector;

• only the inner planes are taken into account, the outer planes are used to shield from background;

• the number of the single-hit signals in a detector $\leqslant 4$ within 900 s;

• the energy deposit corresponding to the second single-hit signal is less than the maximum energy of the ^{12}N beta spectrum (17.3 MeV).

In the BUST data taken in 2012, 60 pairs of events are found to satisfy the above conditions.

While both ^{12}B and ^{12}N radioisotopes obviously contribute to these events, the BUST one-year statistics does not allow us to distinguish between their decays, so that a composite decay rate will be observed. In other words, the reactions initiated by ν_e and $\bar{\nu}_e$ are not separated from each other. Figure 5 illustrates the exponential decay curves corresponding to ${}^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$ and ${}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e$ in comparison with the selected BUST events.

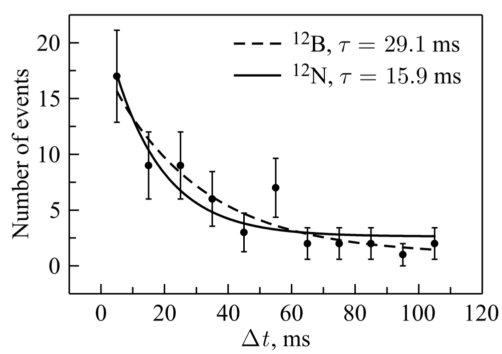

Fig. 5. Exponential decay curves $\sim \mathrm{e}^{-t/\tau}$ for ${}^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$ (dashed) and ${}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e$ (solid). The solid circles are the experimental data of the BUST taken in 2012

In order to search for a possible GRB neutrino signal, we conducted a time correlation analysis using the selected data and the list of GRBs collected by the SWIFT experiment during 2012 [5]. The goal of this analysis was to search for the number of events coinciding in time with a GRB within a given time window. In total, 97 gamma-ray bursts and 60 BUST pairs of events have been selected. We used a time window ± 1000 s with respect to the start time of the GRB and the time of the first hit in a pair of events. No excess of events associated with GRB was observed.

CONCLUSION

Results of an experimental search for neutrinos ejected from gamma-ray bursts in the energy range from 20 to 100 MeV at the Baksan Underground Scintillation Telescope are presented. In the analysis, we looked for neutrinos in time coincidence with a gamma-ray burst. A time correlation analysis of the pairs of the single-hit events due to the reactions $\bar{\nu}_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{B} + e^+$ and ${}^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$ as well as $\nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-$ and ${}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e$ in coincidence with 97 gamma-ray bursts recorded during 2012 by SWIFT was performed. No signal associated with GRB in the time window ± 1000 s is found at the BUST.

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