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SEARCH FOR HIGH-ENERGY MUON NEUTRINOS FROM SOUTHERN HEMISPHERE GAMMA-RAY BURSTS WITH BUST

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The search for muon neutrinos with energy $\geqslant 1$ GeV correlated with Gamma-Ray Bursts (GRBs) has been carried out at the Baksan Underground Scintillation Telescope (BUST). Between December 1978 and December 2013, more than 1500 localized gamma-ray bursts that occurred in the field of view of the BUST were coincident with the BUST operation periods. No neutrino signal from GRBs was detected. Upper limits on associated gamma-ray burst neutrino production are presented.

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INTRODUCTION

Gamma-ray bursts are short and very intense flashes of high-energy gamma rays, which occur unpredictably and isotropically over the sky [1–4]. A considerable portion of the total energy may be carried away by neutrinos created during the burst (see, for example, [5] and references therein). Unlike the GRB photons, which may scatter or be absorbed before they reach the Earth, the neutrinos, due to their small interaction cross section, arrive at the Earth virtually unaffected. Thus, studying neutrinos from GRBs can provide valuable insight into the processes underlying these phenomena.

This paper presents results of a direction-time correlation analysis between the GRBs and BUST events using an upward-going muon data sample.

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1. THE BUST AND DATA TAKING

The Baksan Underground Scintillation Telescope is located in an excavation of $24 \times 24 \times 16$ m under the slope of Mt. Andyrchy (North Caucasus, 43.28°N and 42.69°E) at 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 [6]. The BUST was designed to solve a number of physical problems which predetermined its construction and location [7]. It is a four-story structure with the dimensions of $16.7 \times 16.7 \times 11.1$ m. The distance between the floors is 3.6 m. All six of the outer and the two inner planes of the building are fully covered with standard scintillation detectors. The standard scintillation detector consists of an aluminum tank with the dimensions of $0.7 \times 0.7 \times 0.3$ m filled with a liquid scintillator on the base of white spirit. The total number of detectors is 3180. Every counter is viewed by one PMT (a 15-cm diameter photocathode). The construction of the BUST allows one to identify tracks of muons crossing the telescope. Separation of arrival directions between upper and lower hemispheres is carried out using the time-of-flight method with the time resolution $\simeq 5$ ns [8, 9]. Figure 1 shows the first upward-going muon observed at the BUST. It was shown [8] that in 95% of events, values of the inverse reconstructed particle velocity $1/\beta$ lie in the range of 0.7–1.3 for single downward-going muons. This interval, but with a negative sign of velocity, is used to select the upward-going muons generated by the charged current neutrino interactions in the lower hemisphere. Selection criteria of neutrino events in the BUST cut off particles with energies below 1 GeV.

The angular resolution of the BUST for the reconstructed events is about 1.6°. It should be noted that the direction of an upward-going muon is strongly correlated with the incident neutrino direction. The rms angle between a muon and

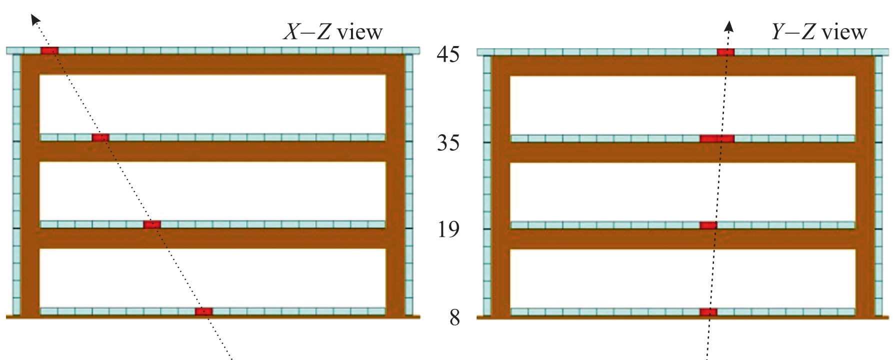

Fig. 1. The first upward-going muon observed at the BUST (December 14, 1978). The relative time of flight of the horizontal planes is shown

its parent neutrino is $\simeq 3.7°$, assuming an atmospheric neutrino spectrum. As the assumed GRB neutrino spectra are harder than the atmospheric one, a smaller angular separation between the muons and GRBs can be expected.

The data used in this work were collected during 1978–2013 years with a lifetime of 27.72 y. In this period, 1474 upward-going muons (with $\theta > 90°$) were detected. For this analysis we selected 1357 events with $\theta > 100°$. This criterion is used to reduce background from the downward-going atmospheric muons scattered at large angles in the rock.

2. GRB-NEUTRINO CORRELATION ANALYSIS

A comprehensive gamma-ray burst catalog does not exist to date. The list of localized GRBs (3982 localized GRBs over the years 1978–2013) was obtained from different catalogs [10]. 3690 localized GRBs coincided with the BUST operation periods, 1532 GRBs of which occured in the field of view of the BUST ($\theta > 100°$). Figure 2 shows our neutrino events and the selected GRBs as a function of the year.

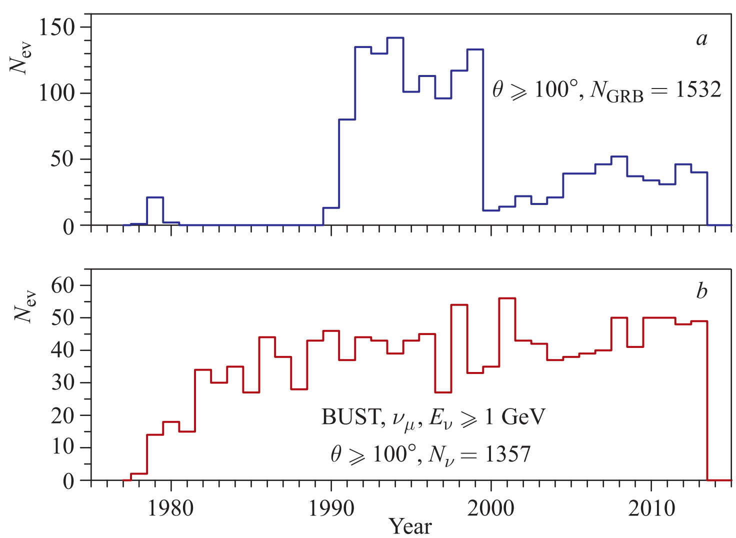

Fig. 2. Gamma-ray bursts (*a*) and the BUST events (*b*) as a function of year

We consider possible time and directional correlation between the BUST neutrino events and GRBs. Figure 3 shows the difference in time between the detection of an upward-going muon and a GRB ($\Delta t = T_{\rm BUST} - T_{\rm GRB}$) as a function of their angular separation d. We find no muon neutrino events correlated

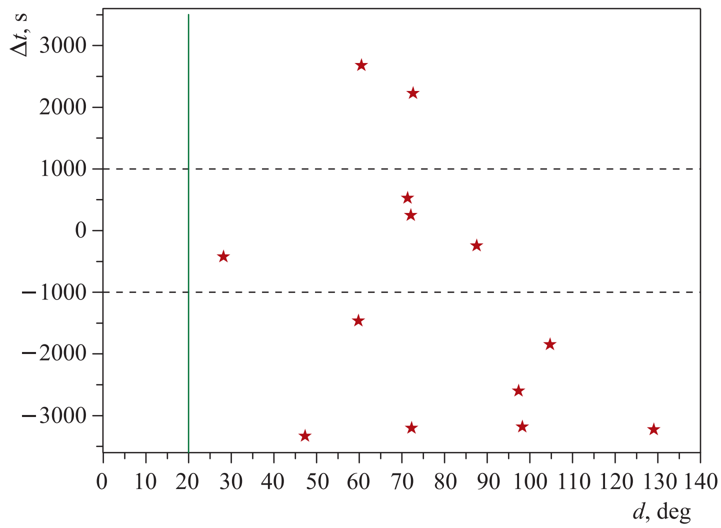

Fig. 3. Difference in detection times vs. the angular separation between the BUST upward-going muon events and GRBs

in time (within 1000 s) and direction (within $d_0 = 20°$) with a GRB. Taking into account the angular resolution of the BUST and rms angle between a muon and its parent neutrino, the value of d_0 corresponds to directional uncertainty $\simeq 19.5°$, which is much greater than directional uncertainty for the selected GRBs.

3. RESULTS

In the absence of any clear neutrino signal from GRBs, model-independent GRB-neutrino fluence upper limits were calculated, following the Green's function method [11]. This method gives the fluence limit on monoenergetic neutrinos at different specific energies; the calculation is repeated at different values of the neutrino energy. The advantage of this method is that an integrated fluence upper limit can be determined for any input spectrum [12].

Following the Green's function method, the 90% confidence level (CL) GRB-neutrino fluence upper limit was calculated as

$$F(E_\nu) = \frac{N_{90}}{S_{\text{eff}}(E_\nu)} = \frac{n_{90}}{S_{\text{eff}}(E_\nu) \cdot N_{\text{GRB}}}, \tag{1}$$

where $n_{90} = 2.3$ and $S_{\text{eff}}(E_\nu)$ is the energy-dependent neutrino effective collecting area. Figure 4 shows the model-independent GRB-neutrino upper limits

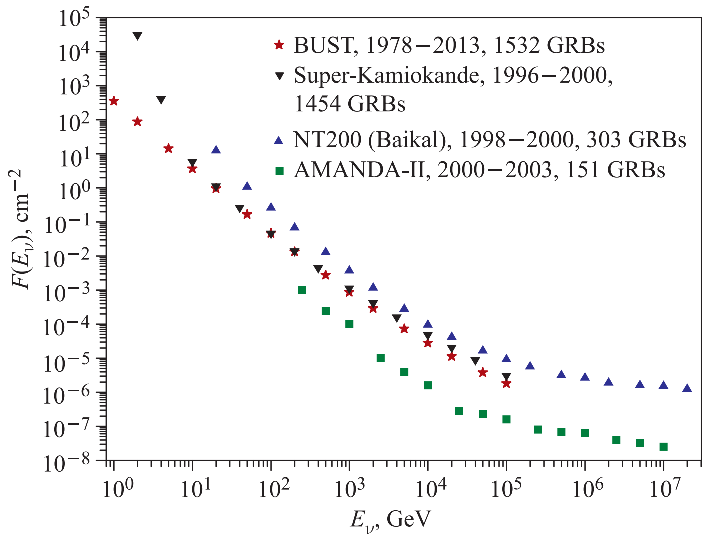

Fig. 4. The Green's function of the 90% CL upper limits on GRB-neutrino fluence per GRB obtained at the BUST (this work), Super-Kamiokande [11], AMANDA [12] and Baikal [13]

on GRB-neutrino fluence per GRB obtained at the BUST in comparison with the results of other experiments.

4. DISCUSSION

Denote the ratio of the mean neutrino numbers per GRB for the BUST and AMANDA as

$$\xi = \frac{N_{\mathrm{BUST}}}{N_{\mathrm{AMANDA}}}. \tag{2}$$

Assuming that the neutrino emission from gamma-ray bursts has a power spectrum $E_\nu^{-\gamma}$ with a single exponent γ in the whole energy range, the dependence of this ratio on γ can be calculated by the formula

$$\xi(\gamma) = \frac{\int\limits_{1}^{10^5} S_{\mathrm{BUST}}(E_\nu) E^{-\gamma} dE}{\int\limits_{250}^{10^7} S_{\mathrm{AMANDA}}(E_\nu) E^{-\gamma} dE}, \tag{3}$$

where $S_{\mathrm{BUST}}(E_\nu)$ and $S_{\mathrm{AMANDA}}(E_\nu)$ are the energy-dependent neutrino effective collecting area of the BUST and AMANDA, respectively. Intersection of the

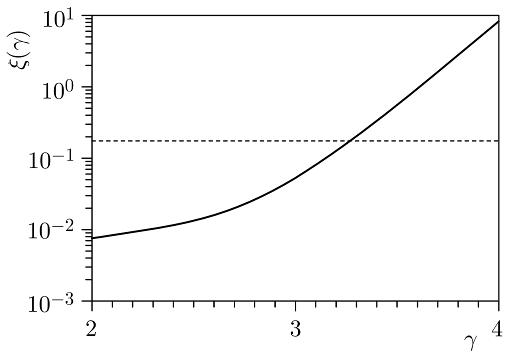

Fig. 5. The ratio of mean neutrino numbers per GRB for the BUST and AMANDA. The solid line is the dependence on γ according to formula (3). The dashed line: $\xi_{\rm exp} = 0.175$

dependence $\xi(\gamma)$ with the value $\xi_{\rm exp} = 0.175$, calculated from the experimentally-obtained constraints, gives $\gamma_\xi \simeq 3.27$ (Fig. 5). Therefore, we can compare limits obtained in different energy ranges and conclude that the BUST limit is more strict if $\gamma > 3.27$.

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