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The Search for Neutrino Events from the Blazar PKS 0735+17 at the Baksan Underground Scintillation Telescope

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The results of searching for neutrino events from the blazar PKS 0735+17 at the Baksan Underground Scintillation Telescope (BUST) are presented. A neutrino from the PKS 0735+17 region was detected at BUST on December 4, 2021, during a strong outburst of this object, coinciding with an observed Fermi LAT gamma-ray outburst. The BUST neutrino event preceded the detections of high-energy neutrino events from the PKS 0735+17 region by IceCube, Baikal-GVD, and KM3NeT.

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1. Introduction

PKS 0735+17 is a bright radio and γ-ray blazar that was in December 2021 observed during a strong flare in the gamma-ray, optical, and radio bands. The flux of the blazar in gamma rays and in the optical band hit its historical maximum. This major flare attracts much interest because it coincides with a simultaneous detection of multiple neutrino events observed by the IceCube, Baikal, Baksan, and KM3NeT neutrino telescopes.

In this paper we present an observation of a lower-energy neutrino candidate event coinciding with a gamma-ray flare of the blazar before the detections of high-energy neutrino events. It is shown that for the astrophysical neutrino spectrum obtained for the IceCube high-energy starting events, there are no large contradiction between BUST and IceCube in neutrino numbers detected from the blazar PKS 0735+17.

2. Experiment

The Baksan Underground Scintillation Telescope (BUST) has been detecting muon neutrinos/antineutrinos from the lower hemisphere with a threshold energy of 1 GeV since 1978 [1].

BUST is a multi-purpose instrument designed for a wide range of studies in neutrino astrophysics and physics of cosmic rays and elementary particles [2–6]. It is located in Baksan Valley (North Caucasus, Russia) in an underground laboratory at an effective depth of 850 m of water equivalent. The telescope with dimensions of $17 \times 17 \times 11$ m^3 consists of 4 horizontal and 4 vertical planes with scintillation counters, the total number of which in BUST is equal to 3184. The standard scintillation counter is an aluminum container with dimensions of $0.7 \times 0.7 \times 0.3$ m^3 filled with organic liquid scintillator based on white spirit as a solvent C_nH_{2n+2} ($n \approx 9$). Each scintillation counter is viewed by a single photomultiplier (PM) tube FEU-49 with a photocathode diameter of 15 cm. The most probable energy deposition of muons in the counter is 50 MeV. Each counter has four output signals. The PM anode signal is used to fix the plane trigger time and to measure its energy deposition up to 2.5 GeV. The current output (an anode signal coming through an integrating circuit) is used to adjust and control the PM gains. The signals from the 12^{th} dynodes feed the inputs of pulse shape discriminators (the so called pulse channel) with threshold amplitudes of 8 and 10 MeV for the inner and outer planes respectively. The signal from the 5^{th} dynode comes to the input of a logarithmic converter, where it is transformed into a pulse whose duration is proportional to the logarithm of the signal amplitude. The logarithmic channel allows the energy release in each detector to be measured within the 0.5–600 GeV energy range.

An actuation of the pulse channel of any BUST counter triggers the data acquisition system. The count rate of such a trigger is 17 s^{-1}. When a trigger appears, all data about a given event come to an online computer, where the preprocessing of events is performed in order to get information about the current state of recording devices. GPS signals with a synchronization accuracy of 0.2 ms are used to bind events to the universal time.

The BUST design allows one to identify the trajectories of the muons crossing the telescope and to determine the muon arrival direction. The angular resolution of the instrument is $\approx 1.6°$. 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 the arrival directions of the muon and its parent neutrino equals $\simeq 3.7°$ for the energy spectrum of atmospheric neutrinos. The cumulative uncertainty in determining the direction of the neutrino, including the angular resolution of the telescope and the very nature of the signal (the angle of muon production with respect to the direction of the neutrino and the multiple scattering of the muon during its passage from the point of production to the facility), is $\simeq 5°$. Since the calculated spectra of the neutrinos from astrophysical sources are harder than those of the atmospheric neutrinos, one could expect a smaller angular distance between the arrival directions of the recorded muons and the direction to an astrophysical object.

When detecting muons from the lower hemisphere ($\theta > 90°$) 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 $\theta > 100°$. 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 sufficiently large thickness of matter [7].

The separation of muon arrival directions 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 the flight between two scintillation planes is measured, equals 3.5 ns and is mainly determined by the counter properties. For single muons from the upper hemisphere, the reconstructed inverse velocity $1/\beta$ ($\beta = v/c$) lies within the range $0.7 \div 1.3$ for 95% of events [8]. The same interval, but with the negative velocity sign, is used to select the muons from the lower hemisphere, generated in the neutrino interactions with the matter (rock) below the telescope. The threshold energy of muon neutrinos detected by BUST is determined by the energy losses of muons crossing the telescope and is equal to 1 GeV for the used selection criteria.

3. Neutrinos from PKS 0735+17

BUST detected an up-going muon neutrino with an energy above 1 GeV from the direction of PKS 0735+17 on December 4, 2021, at 14:52:47.83 UT [9]. The best-fit arrival direction is RA=116.5°, Dec=16.6° that is 2.18° from the source. The event coincided with a gamma-ray flare observed by Fermi LAT and preceded by ~4 days the simultaneous detection from the PKS 0735+17 region of two rare high-energy neutrino events: IceCube (172 TeV) [10] and Baikal-GVD (43 TeV) [11], and by ~11 days the 18 TeV neutrino event detected by KM3NeT [12]. A multi-messenger study of this peculiar blazar dedicated to the investigation of the temporal and spectral changes in the multi-wavelength emission at the time of neutrino event detections was presented in [13]

During the entire observing time (12981.33 days from 1978 to March 31, 2022), only 1 event was detected at BUST from the cell with a radius of 5 degrees centered on PKS 0735+17. A total of 115 events have been recorded for the declination of this blazar plus or minus 5 degrees over the entire right ascension range. Thus, over the entire observation period, the cell could record an average of 3.2 events from the blazar. The probability to accidentally detect 1 or more events from the given cell during a flare (~10 days) is ≈ 0.0025.

4. Discussion

BUST is rather a small-size telescope in comparison with the telescopes of the cubic kilometer scale. But due to the rapid growth of the effective area of neutrino detection with energy (owing to the growth of the cross section of muon neutrino interaction with a nucleon), BUST can in principle detect fluxes comparable to those studied by large telescopes. It depends on specific shape of astrophysical neutrino spectrum and relation of effective areas of neutrino telescopes with energy. Let us take, for example, the astrophysical neutrino spectrum with an unbroken power law:

$$\Phi(E_\nu) \sim E_\nu^{-\gamma}, \tag{1}$$

and the muon neutrino effective collecting area of IceCube from [14]. The effective areas of BUST and IceCube depending on the neutrino energy are shown in Fig. 1.

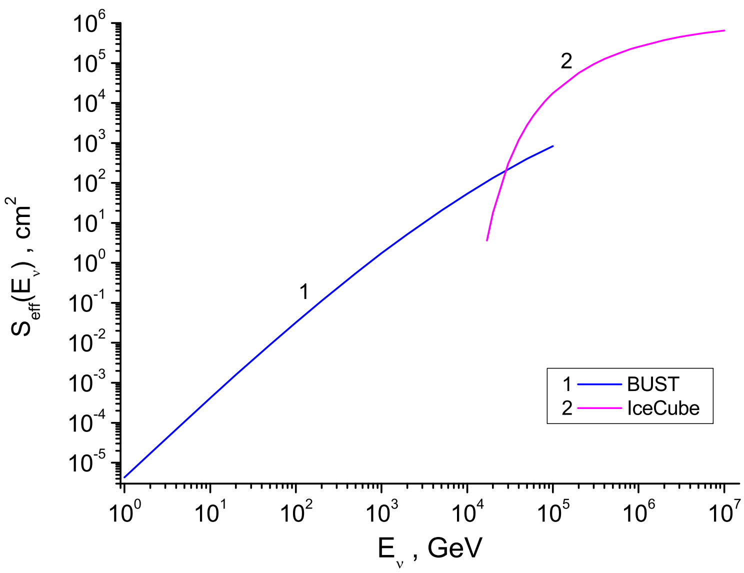

Figure 1: Muon neutrino effective collecting area: 1—BUST; 2—IceCube [14].

Let us denote the ratio of the mean neutrino numbers from the direction of PKS 0735+17 for BUST and IceCube as:

$$\xi = \frac{N_{BUST}}{N_{IceCube}}, \tag{2}$$

with the experimental value $\xi_{exp} = 1.0$.

Assuming that the neutrino emission from blasars has a power spectrum with a single exponent γ in the whole energy range, the dependence of this ratio on γ can be calculated by the formula:

$$\xi(\gamma) = \frac{\int_{E_1^B}^{E_2^B} S_{BUST}(E_\nu)E_\nu^{-\gamma}dE}{\int_{E_1^I}^{E_2^I} S_{IceCube}(E_\nu)E_\nu^{-\gamma}dE} \tag{3}$$

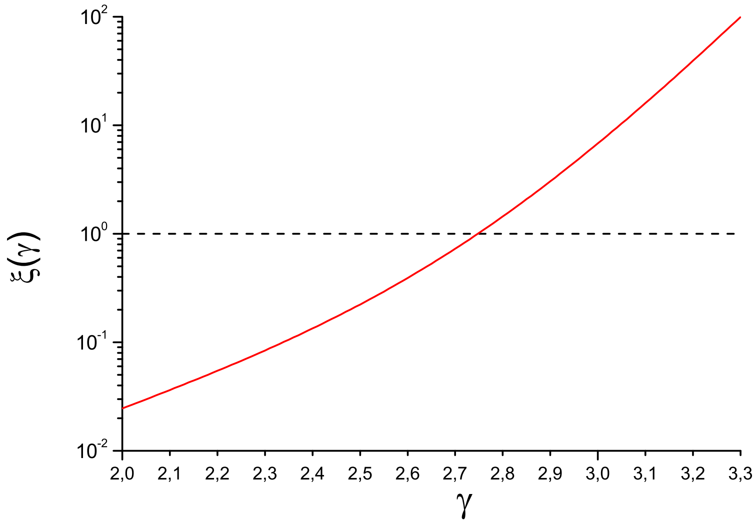

Figure 2: The ratio of the mean neutrino numbers for BUST and IceCube. The solid line is the dependence on γ according to formula (3). The dashed line is $\xi_{exp} = 1.0$

where $S_{BUST}(E_\nu)$ and $S_{IceCube}(E_\nu)$ are the energy-dependent muon neutrino effective collecting area of BUST and IceCube respectively. The limits of integration are taken as $E_1^B = 1$ GeV, $E_2^B = 10^5$ GeV, $E_1^I = 1.7 \times 10^4$ GeV, $E_2^I = 10^7$ GeV.

As can be seen from Fig. 2, the intersection of the $\xi(\gamma)$ dependence with the value $\xi_{exp} = 1.0$ gives $\gamma \simeq 2.75$. It is worth noting that the astrophysical neutrino spectrum obtained for the IceCube high-energy starting events is compatible with an unbroken power law, having a preferred spectral index of $2.87^{+0.20}_{-0.19}$ for the 68.3% confidence interval [15].

Therefore for this astrophysical neutrino spectrum, there is no large contradiction between BUST and IceCube in the neutrino numbers detected from the blasar PKS 0735+17.

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