Carpet-2 Search for Gamma Rays above 100 TeV
in Coincidence with HAWC and IceCube Alerts

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We report on the search of astrophysical gamma rays with energies in the 100 TeV to several PeV range arriving in directional and temporal coincidence with public alerts from HAWC (TeV gamma rays) and IceCube (neutrinos above \( \sim 100 \) TeV). The observations have been performed with the Carpet-2 air-shower detector at the Baksan Neutrino Observatory, working in the “photon-friendly” mode since 2018. Photon candidate showers are selected by their low muon content. No significant excess of the photon candidates have been observed, and upper limits on gamma-ray fluences associated with the alerts are obtained. For events with good viewing conditions, the Carpet-2 effective area for photons is of the order of the IceCube effective area for neutrinos of the same energy, so the constraints start to probe the production of neutrinos in fast flares of Galactic sources.

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Over the last decade, multimessenger astronomy has brought several bright results of great importance, notably the identification of a binary neutron star merger in gravitational-wave and electromagnetic channels [1] and a possible association of a high-energy neutrino event with a blazar flare [2]. These and other important observations became possible thanks to alerts distributed by gravitational-wave, neutrino and conventional astronomical observatories to the worldwide community of observers detecting signals in various channels and electromagnetic bands. Up to now, in the electromagnetic channel, these alerts have been followed up at the energies up to \( \sim 100 \) TeV, above which the sensitivity of the highest-energy participating observatory, HAWC, fades, while higher energies have been accessible only for the neutrino and cosmic-ray channels.

In the dominant part of the scenarios of the astrophysical production of high-energy neutrinos, they are born in \( \pi^\pm\)-meson decays, while the decays of \( \pi^0\) mesons result in the accompanying gamma rays of similar energies. The 100–1000-TeV photons efficiently produce \( e^+e^-\) pairs on the cosmic microwave background [12], so the mean free path of these photons does not exceed the size of the Milky Way. Therefore, photons of these energies cannot reach us from active galactic nuclei (see, e.g., [13] for a discussion of models), nor from putative neutrino production regions in the intergalactic space [14, 15]. Any observation of gamma rays at these energies associated with neutrinos would either imply Galactic sources [16, 17] or, if the event is directionally associated with an
extragalactic object, suggest new particle physics affecting the transparency of the Universe to high-energy gamma rays [18].

Previously, we reported [19] on the analysis of the data above 1 PeV accumulated by Carpet-2 during 1999–2011, when the main task of the experiment was related to cosmic-ray studies. We obtained constraints on the neutrino flux from directions of IceCube neutrinos assuming the sources are steady, because the data time spans did not overlap. Since 2018, Carpet-2 returned to data taking, now as a gamma-ray observatory: changes in the trigger and in the data analysis allowed us to significantly improve the efficiency and to lower the threshold energy for gamma-ray studies, see, e.g., [20]. Here, we report for the first time on the results of simultaneous observations of the alerts at energies above 100 TeV.

IceCube issues public alerts corresponding to detections of individual muon-track events passing certain criteria since 2017, see the description of “EHE” and “HESE” alerts (2017–2019) in [21] and of “GOLD” and “BRONZE” alerts (since 2019) in [22]. Most of the alert events have estimated energies between 100 TeV and 1 PeV. The criteria are chosen to maximize the probability that the event is of astrophysical origin. Still, many of them are background atmospheric events: the astrophysical purity of the “GOLD” sample is only 50%, that of the “BRONZE” sample is 30%.

Another window into sub-PeV astrophysics is provided by observations of gamma rays at slightly lower energies in the TeV range. In parallel with pointing observations by atmospheric Cerenkov telescopes, air-shower installations monitor the sky continuously. In particular, HAWC has recently started to issue various public alerts when a significant point-like signal is observed during one daily passage of the “flare” direction through the HAWC field of view, see [23] for more details. These alerts are of particular interest because the energies are very close to the band we study here, and a discovery of a flaring Galactic source in this energy range would have important astrophysical consequences.

We report here on the results of 2.5 years of following up these HAWC and IceCube alerts with Carpet-2, see [24, 25] for the description of the experiment. Since Carpet-2 is an air-shower detector, it operates continuously and observes a large fraction of the sky. Therefore, it does not need to be pointed to the alert direction, so the alerts are analyzed offline. The search is based on the set of photon candidate events that are selected as muon-poor air showers, as described in [19, 20, 26]. The photon detection efficiency and the angular resolution were determined by the Monte-Carlo simulations; together with the photon-candidate selection cuts for the energies $E > 300$ TeV they are discussed in detail in [20] (“Dataset II”). Here, we extend the analysis down to 100 TeV energies because the combined directional and temporal selection reduces efficiently the hadronic background, which otherwise is the main problem in the search for gamma rays with Carpet-2 below 300 TeV. Photon candidate events are selected by their reconstructed number of charged particles, $N_e$, and the number of muons in the 175 m$^2$ muon detector, $N_\mu$. It was found optimal to consider only muonless events for these energies, though at higher energies the cut was determined in terms of the ratio $N_\mu/N_e$. The criteria are given in Table 1 together with the number of photon candidate events in the data sample and the efficiency of the gamma-ray selection cuts (determined as the ratio of Monte-Carlo photons with reconstructed $N_\mu, N_e$ satisfying the selection conditions to the total number of reconstructed Monte-Carlo photons). The candidates were selected from 52791 air showers, recorded between April 8, 2018, and October 26, 2020, successfully reconstructed and passing the quality cuts. The number of live days in this period was 675.

| Energy, TeV | Min. $N_e$ | Max. $n_\mu/N_e$ | Selection efficiency | Number of events |
|------------|------------|------------------|---------------------|-----------------|
| >100       | $10^4.2251$ | 0                | 0.995               | 1021            |
| >300       | $10^4.6372$ | 0                | 0.509               | 598             |

Carpet-2 dataset consists of events observed with zenith angles up to 40°, but the efficiency decreases rapidly for inclined showers. We select the alerts with declinations between $+5^\circ$ and $+76^\circ$ so that the maximum elevation corresponds to a zenith angle not exceeding $35^\circ$. In addition, we drop the events arrived at the days when our data were not recorded because of maintenance. In this way, we arrive at the list of 9 HAWC alerts and 22 IceCube alerts presented in Table 1 in the Supplementary Material.

Most of the alert directions, however, were outside the Carpet-2 field of view at the time of the event, but they passed through the field of view during the day. We therefore determine time windows of 24 h and of 30 days, centered at the event moment, to search for coinciding gamma-ray candidates. The angular window, as discussed before [20], was set to the 90% CL angular resolution, which at these energies is about $6.15^\circ$. The expected number of candidate events was calculated by randomizing arrival times of photon candidates in the sample.
For each particular alert, we present the expected and observed numbers of the events, the estimated flux within the selected time window and the fluence in Tables 2, 3 in the Supplementary Material. Note that the flux estimates depend crucially on the time window, which is chosen more or less arbitrarily, while the most interesting physical quantity for a burst is the fluence. No significant excess of photon candidates was found, and we present 95% CL upper limits on the flux and fluence. These limits vary strongly from one alert to another because of the strong dependence of the reconstruction efficiency for photons on the zenith angle. In all cases, we are close to the “zero signal, zero background” regime, which motivates us to use stacking to improve sensitivity, and stacked results for all HAWC alerts and all IceCube alerts are also presented in the same tables.

A weak, two-sigma excess, 8 events observed for 4.25 expected, is found at $E > 100 \text{ TeV}$ for stacked IceCube events, dominated by the 200911A alert. This excess is consistent with expected fluctuations, given multiple trials.

Directions of two IceCube events, 190331A and 191215A, were in the Carpet-2 field of view at the neutrino arrival times, which allows us to estimate directly their fluence assuming a fast flare. We use the time window of 1000 s for these two alerts. For good viewing conditions, that is small zenith angles, the effective area of Carpet-2 in the configuration used for the photon search in the present analysis is of the same order as the effective area of IceCube for neutrinos of similar energies (see Fig. 1). Therefore, the fluence upper limits of order 1 GeV/cm², see Tables 2–4 in the supplementary material, start to constrain the origin of neutrinos in fast flares of Galactic sources. Assuming flares longer than a few hours, we obtain less constraining limits because the arrival direction of the alert event leaves the field of view of Carpet-2. All HAWC alerts happen outside of the Carpet-2 field of view because of the difference in geographical longitudes of the two installations.

The program of multimessenger observations with Carpet-2 continues. Besides HAWC and IceCube alerts, it includes also LIGO/VIRGO alerts and low-energy neutrino burst alerts from the Baksan Underground Scintillator Telescope. Soon, when Baikal-GVD high-energy neutrino alerts become available, they will join the list. At the same time, the upgrade of the installation to Carpet-3 is ongoing with an order of magnitude increase in the collection area and more than a twofold increase in the area of the muon detector. This will allow reaching the sensitivity in the sub-PeV gamma rays at the level of the corresponding neutrino sensitivity of IceCube not only for short flares, but also for long-term observations and for the diffuse flux.

**SUPPLEMENTARY INFORMATION**

The online version contains supplementary materials available at https://doi.org/10.1134/S0021364020240029.

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