Carpet–2 search for PeV gamma rays associated with IceCube high-energy neutrino events

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Carpet–2 is an air-shower array at Baksan Valley, Russia, equipped with a large-area (175 m\textsuperscript{2}) muon detector, which makes it possible to separate primary photons from hadrons. We report the first results of the search for primary photons with energies \( E_{\gamma} > 1 \) PeV, directionally associated with IceCube high-energy neutrino events, in the data obtained in 3080 days of Carpet–2 live time.

1. MOTIVATION

The origin of high-energy (\( E \gtrsim 100 \) TeV) astrophysical neutrinos detected in recent years by the IceCube experiment\textsuperscript{[1] 2 3 4 5 6 7 8} remains one of the most intriguing problems in modern astroparticle physics (see e.g. Ref.\textsuperscript{[9]} for a review). The arrival directions of these neutrinos do not demonstrate any significant excess towards the Galactic disk, see e.g.\textsuperscript{[8] 10]}, as it would happen for most models of Galactic sources, while serious tensions with Fermi-LAT observations of the diffuse gamma-ray flux are present for extragalactic source models, see discussions in Ref.\textsuperscript{[9]} and below. A recent observation of a coincidence of one neutrino event with a blazar flare\textsuperscript{[11]} does not add much to the picture: even if the association is physical, non-observations of candidate sources for \( \sim 40 \) similar events in the IceCube data set, together with constraints from diffuse gamma rays and the lack of clustering of neutrino events, constrain the contribution of similar blazars to \( \lesssim 10\% \) of the total astrophysical neutrino flux\textsuperscript{[12] 13}. We therefore need additional diagnostic tools to shed light on the origin of high-energy neutrino events.

In most astrophysical scenarios which do not involve particle physics beyond the Standard Model, high-energy neutrinos are produced in decays of charged \( \pi \) mesons. These mesons are, in turn, born in hadronic and photohadronic processes, where produced \( \pi^{\pm} \)’s are always accompanied by \( \pi^0 \)’s. The latters decay immediately to photon pairs, therefore providing for accompanying gamma-ray fluxes similar to those of neutrinos. This simple scheme justifies the \textit{multimessenger approach}: the fluxes of cosmic rays which launch the process, gamma rays and neutrinos appear to be related in a straightforward way, so that their joint observations constrain source models efficiently.

Energetic gamma rays produce electron-positron pairs when propagating through the background radiation\textsuperscript{[14]}. The mean free path is minimal for photons with energies \( E_{\gamma} \sim (0.1 \div 10) \) PeV, similar to those of IceCube neutrinos, because these gamma rays produce pairs on the most abundant Cosmic Microwave Background photons. The mean free path of gamma rays with these energies is of order of the size of a galaxy, and therefore they become an important diagnostic tool for the origin of neutrinos\textsuperscript{[15] 16 17}: accompanying photons from Galactic sources arrive to the observer without a significant attenuation, while those from beyond the Galaxy lose their energy in the pair-production processes. In the latter case, resulting electrons and positrons launch electromagnetic cascades of inverse Compton scattering and further pair production, in which the entire energy of the initial \( \sim \)PeV gamma ray is transformed into photons with \( E_{\gamma} \sim 10 \) GeV, for which the Universe is transparent. These photons contribute to the extragalactic diffuse background measured by Fermi LAT\textsuperscript{[18]}. Since their contribution cannot exceed the total measured value of the diffuse flux, the energy emitted in \( \sim \)PeV photons in the Universe is constrained. For the \( \pi \)-meson production mechanism, this constrains also the energy in neutrinos. It appears that the observed flux of IceCube neutrinos at energies below \( E_{\nu} \sim 200 \) TeV is in serious tensions with this constraints, if the standard production mechanism in extragalactic sources is assumed (see e.g. Ref.\textsuperscript{[9]} for more details). This suggests that a...
significant part of the astrophysical neutrinos observed by IceCube should come from our Galaxy, and their accompanying (sub)PeV photons should arrive to the Earth unattenuated. Indeed, some indications exist for a turnover in the Fermi-LAT diffuse gamma-ray spectrum at highest energies, consistent with the corresponding unabsorbed component. However, the highest-energy points in the spectrum correspond to a few TeV, that is orders of magnitude lower than the energies studied at IceCube.

It is an experimentally complicated task to perform a wide-scale search for higher-energy cosmic photons. Indeed, in the TeV domain, atmospheric Cerenkov telescopes have quite narrow fields of view, while at even higher energies, extensive air shower (EAS) arrays experience difficulties in separation between primary photons and hadrons. Presently, very few experiments in the world are sensitive to \(~\text{PeV}\) photons. The aim of the present work is to report the results of the first multimessenger study of IceCube neutrinos with PeV gamma rays.

2. THE CARPET–2 EXPERIMENT AS A PEV GAMMA-RAY TELESCOPE

The results we report here have been obtained with the Carpet–2 experiment at the Baksan Neutrino Observatory of INR RAS. A more detailed description of the experiment may be found in Refs. \[20, 21, 22, 23\]. Carpet–2 is an EAS array constructed and developed for simultaneous measurements of the electromagnetic, muonic and hadronic components of air showers induced by cosmic particles with primary energies above 50 TeV. It consists of the central unit (400 individual liquid-scintillator detector stations forming a continuous “carpet” of the total area of 200 m²), 6 remote stations (scintillator detectors of 9 m² area in each station, separated by 30 to 40 m from the center of the main unit), neutron detectors and a large-area underground muon detector (MD), which is the key element for the present study. In the configuration used for the present analysis, the area of MD was 175 m². It consists of a continuous array of individual plastic-scintillator detectors located in the underground tunnel covered by 2.5 m of soil. This corresponds to the detection threshold of 1 GeV for vertical muons. The arrival directions of air showers are determined with the help of remote detectors. For the analysis, showers with reconstructed axes inside the central unit (excluding border detectors) were selected. The shower size \(N_e\) was determined by fitting the particle densities measured by individual detector stations in the central unit to the Nishimura–Kamata–Greisen (NKG) \[24, 25\] profile with the fixed shower age \(s = 1\),

\[
f(r) = \frac{5}{4\pi} \frac{N_e}{R^3_M} \left( \frac{r}{R_M} \right)^{-1} \left( 1 + \frac{r}{R_M} \right)^{-3.5},
\]

where \(r\) is the distance between the measurement point and the shower axis and \(R_M \approx 95\) m is the Moliere radius. The observable of MD is the total number of muons recorded in the 175 m² detector, \(n_\mu\). For the purposes of the present work, therefore, each event is characterised by the arrival direction (the azimuthal, \(\phi\), and zenith, \(\theta\), angles), the arrival time, \(N_e\) and \(n_\mu\). Events satisfying the following criteria were included in the data set:

- the number of central-unit detectors with nonzero readings is \(\geq 300\);
- the total signal in the central unit is \(\geq 10^4\) relativistic particles;
- \(1 < n_\mu < 250\).

The latter cut deserves some comments. The installation was initially constructed for the study of the structure of hadronic EASs near the core and not for gamma-ray astronomy. Therefore, for the main part of the data set, the condition \(n_\mu > 1\) was included as a trigger requirement. As we will see immediately, this is not the optimal cut for gamma-ray searches as at low energies, many gamma-ray events do not satisfy it. It is this cut which determines the lower energy threshold of \(E_\gamma = 1\) PeV used in the present analysis. The cut \(n_\mu < 250\) is determined by the detector saturation.

Muons in EAS are produced dominantly in decays of charged mesons born in hadronic interactions. Gamma-ray induced showers are mostly electromagnetic and therefore are muon-poor compared to hadronic ones \[25\]. We use this feature to search for candidate events with gamma-ray primaries in the data. To determine the cuts separating primary photons and hadrons, we perform Monte-Carlo (MC) simulations of air showers based on the CORSIKA 7.4003 \[27\] simulation package with QGSJET-II 01c \[28\] and FLUKA2011.2c \[29\] as hadronic-interaction models. We note in passing that for gamma rays of \(\sim\text{PeV}\) energies, the description of the shower development is insensitive to the choice of the hadronic model. The spectrum for primary photons \(\propto E_\gamma^{-2}\) was assumed while for hadrons, the spectrum was tuned to reproduce the observed \(N_e\) distribution. The arrival directions were assumed to be isotropic; the simulations have been performed without thinning. For each artificial shower, random positions of the axis in the installation were assumed and the response of individual detectors was simulated with a dedicated MC code. Air-
Search for PeV gamma rays associated with IceCube events

3. DATA SETS, ANALYSIS AND RESULTS

IceCube data. The main part of the study is the search for PeV photons from a stacked sample of hypothetical sources of IceCube neutrino events. We use all published IceCube arrival directions of high-energy starting (HESE, Refs. [3, 5, 8]) and muon-track [4, 5, 6, 7] events, supplemented by later online alerts [31]. A useful compilation of events is given in Ref. [32]. We impose a constraint that the arrival direction is determined with a precision of better than 3° and is in the part of the sky which Carpet–2 can see (limited by \( \theta \leq 40° \)). The catalog of resulting events is given in Table 1.

Carpet–2 data. We use 3080 live days of Carpet–2 data recorded between 1999 and 2011, in total 115821 events passing the cuts described above. The photon candidate criteria select 523 events which we use for the stacked-source analysis, see Fig. 2. In addition, in 2016–17, the installation was operating for some periods of time in between works on its upgrade (also limited by the damage from a natural disaster of September 1, 2017); however, no useful MD data were recorded for this time. Since April 7, 2018, Carpet–2 is working with the new trigger optimized for gamma-ray searches (the \( n_\mu > 1 \) condition is no longer applied). All data of 2016–2018 were used to search for coincidences with IceCube alerts, but not for the stacked search.

Stacked IceCube directions. First, we determine the angular resolution of the installation from MC

\[
S \int dt \, \epsilon(\theta(t)) \cos \theta(t),
\]

where \( S = 162 \, \text{m}^2 \) is the collecting area of the central unit.
| ID  | R.A.  | DEC  | Error |
|-----|-------|------|-------|
| HES13 | 67.9  | +40.3 | 1.2   |
| HES38 | 93.34 | +13.98| 1.2   |
| HES47 | 209.36| +67.38| 1.2   |
| HES62 | 187.9 | +13.3 | 1.3   |
| HES63 | 160.0 | +6.5  | 1.2   |
| HES82 | 240.9 | +9.4  | 1.2   |
| DIF2  | 298.21| +11.74| 0.45  |
| DIF4  | 141.25| +47.80| 0.43  |
| DIF5  | 306.96| +21.00| 2.13  |
| DIF7  | 266.29| +13.40| 0.54  |
| DIF8  | 331.08| +11.09| 0.55  |
| DIF10 | 285.95| +3.15 | 1.09  |
| DIF12 | 235.13| +20.30| 1.71  |
| DIF13 | 272.22| +35.55| 0.85  |
| DIF16 | 36.65 | +19.10| 1.96  |
| DIF17 | 198.74| +31.96| 0.96  |
| DIF20 | 169.61| +28.04| 0.85  |
| DIF23 | 32.94 | +10.22| 0.52  |
| DIF24 | 293.29| +32.82| 0.56  |
| DIF25 | 349.39| +18.05| 2.70  |
| DIF27 | 110.63| +11.42| 0.37  |
| DIF28 | 100.48| +4.56 | 1.08  |
| DIF29 | 91.60 | +12.18| 0.40  |
| DIF30 | 325.5 | +26.1 | 1.62  |
| DIF31 | 328.4 | +06.00| 0.55  |
| DIF32 | 134.0 | +28.00| 0.45  |
| DIF33 | 197.6 | +19.9 | 2.33  |
| DIF34 | 76.3  | +12.6 | 0.66  |
| DIF35 | 15.6  | +15.6 | 0.53  |
| EHE3  | 46.58 | +14.98| 0.78  |
| EHE5  | 77.43 | +5.72 | 0.83  |
| EHE6  | 340.0 | +7.40 | 0.47  |
| AHEs1 | 240.57| +9.34 | 0.60  |
| AHEs4 | 40.83 | +12.56| 0.88  |

Table 1: The catalog of 34 IceCube events used for the analysis. ID corresponds to Ref. 32, R.A. and DEC are equatorial coordinates in degrees. The last column gives the uncertainty in the arrival direction (in degrees).

4. CONCLUSIONS AND OUTLOOK

We have presented the first ever limits on PeV photons coming from the arrival directions of IceCube high-energy neutrino events. These limits may be used to constrain potential models of the neutrino origin in Galactic point sources. Alternatively, if the extragalactic origin of neutrinos is independently assumed, these results could constrain new-physics models affecting
gamma-ray propagation (see e.g. Ref. [34] for a review), as it was suggested in Ref. [35].

The lack of Galactic-disk excess in IceCube data constrains the potential contribution of known Galactic point sources, and purely diffuse models of neutrino production in either the Galactic halo [36, 37] or in local sources [19, 38] were put forward in order to reconcile Fermi-LAT limits with the lack of disk anisotropy. These models will be tested by the search of energetic diffuse gamma rays. While Carpet-2 constraints on the diffuse gamma rays will be reported elsewhere, we note that the best sensitivity will be achieved with the upgraded Carpet-3 installation with the muon detector of 410 m$^2$ and additional surface detector stations, both enlarging the effective area of the installation and improving drastically the gamma-hadron separation. Carpet-3 is assembled and will start data taking in 2019. At the same time, the data recorded with the new, “photon-friendly”, trigger are being taken now and will be used to lower the threshold of the gamma-ray searches from 1 PeV to $\sim$ 100 TeV primary energy.

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