

# Search for diffuse cosmic gamma rays of energy $E_\gamma > 100$ TeV with the Carpet-3 air shower array

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**Abstract.** An experiment for measuring the flux of gamma rays of cosmic origin with energy above 100 TeV is currently being prepared at the Baksan Neutrino Observatory (the Carpet-3 experiment). The experiment performance will be accomplished after radical modernization of the existing array by substantially increasing areas of both the muon detector and ground level shower array. In this work some results of calculations of efficiency of the experiment for showers from primary gamma rays are presented for different configurations of the array. It is demonstrated that by increasing the muon detector area up to 615 m<sup>2</sup> (the maximum possible value) one can reach with Carpet-3 the world-best sensitivity to 100 TeV gamma rays. The preliminary values of upper limits on the flux of cosmic diffuse gamma rays with energy higher than 1.3 PeV are also presented, derived from experimental data of the Carpet-2 shower array for a net exposure time of 9.2 years.

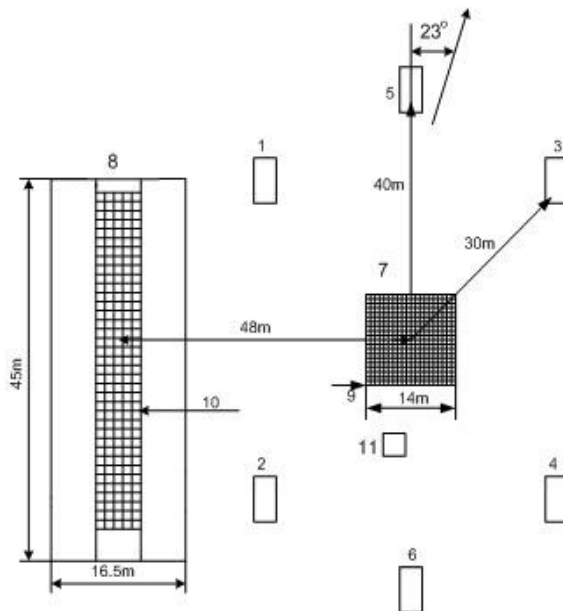
## 1. Introduction

Search for primary gamma rays of energies higher than 100 TeV using the extensive air shower (EAS) method started in 1960s. As opposed to cosmic rays (protons and nuclei of heavier elements) that are charged particles and deflect in interstellar magnetic fields, the primary gamma rays can give information about the spatial distribution and characteristics of places of acceleration of cosmic rays, as well as about the density of cosmic rays in the interstellar space. Investigation of diffuse gamma rays at such energies is carried out by the EAS method in experiments in which one can separate the showers produced by primary photons and nuclei. Such a separation is possible due to the fact that showers from primary photons are essentially less abundant with hadrons (and, as a result, they are muon-poor) in comparison with showers from primary protons and nuclei. Thus, if one selects hadron-poor or muon-poor EAS, there is a hope to effectively distinguish between the showers produced by primary gamma rays and by nuclei. Maze and Zavadski [1] were the first who put forward the idea of searching for high-energy gamma rays by way of detecting muon-poor showers. The experiments at Mt. Chacaltaya [2], Tien-Shan [3], and Yakutsk [4] published such results, but those had insufficient statistical significance and were not confirmed later. More careful subsequent experiments (collaborations EAS-TOP [5], and KASCADE [6] in the energy range  $3 \cdot 10^{14} - 5 \cdot 10^{16}$  eV, and Haverah Park [7], Yakutsk [8] at energies higher than  $10^{18}$  eV) yielded only upper limits on the fluxes of cosmic gamma rays. In all these experiments only upper limits on the fluxes have been obtained, that appeared to be much lower than the fluxes of diffuse cosmic gamma rays supposedly measured in

earlier works. In the MSU experiment [9] the search for showers from primary gamma rays in region of energies  $5 \cdot 10^{15} - 2 \cdot 10^{17}$  eV, made by the method of selection of moonless showers, also yielded only upper limits with an exception of the region  $5 \cdot 10^{16} - 10^{17}$  eV. In this region some muonless showers were detected, whose number considerably exceeded an expectation for background events, which allowed one to derive a value of the flux of diffuse gamma rays with such energies. It should be noticed, however, that in the KASCADE-Grande experiment [10] in the same energy region of primary energies only flux limits for diffuse gamma rays have been obtained, and they contradict to the results of MSU

## 2. Experimental

The Carpet-2 air shower array [11, 12] of the Baksan Neutrino Observatory is located in the North Caucasus region near Mount Elbrus at an altitude of 1700 m above sea level (atmospheric depth 840 g/cm<sup>2</sup>) (figure 1).



**Figure 1.** The layout of the Carpet-2 multipurpose air shower array: 1-6 are outdoor huts with scintillators, 7 is the Carpet, 8 is the muon detector, and 9 is a neutron monitor.

The geomagnetic cutoff rigidity corresponds to 5.6 GV. The array consists of a ground level detector called the Carpet (200 m<sup>2</sup>), six outdoor huts with 9 m<sup>2</sup> of scintillation detectors in each, an underground muon detector and a neutron monitor. The Carpet consists of 400 liquid scintillation detectors, each of 0.5 m<sup>2</sup> area. The range of energy release measured by a single detector is 10-5000 relativistic particles (r.p). One r.p. is the most probable energy release produced by a cosmic ray particle crossing the detector, and it equals 50 MeV. Six outdoor huts have 18 scintillator detectors of the same type. Four of them are placed in the form a square at a distance of 30 m from the array center. The signals from these detectors are used as stopping pulses for the time measurement system to measure delays and reconstruct the arrival direction. The Carpet can measure the shower parameters with a good accuracy:  $\Delta X = \Delta Y = 0.35$  m,  $\Delta N_e / N_e = 0.1$  in the EAS size interval  $N_e = 10^5 - 5 \cdot 10^6$ . The MD is located at a distance of 48 m from the array center; it is arranged in an underground tunnel at a depth of 500 g/cm<sup>2</sup>, which corresponds to the energy threshold of 1 GeV. The muon detector (MD) is an extended plane with dimensions  $5 \times 35$  m, and it consists of 175 plastic scintillation counters of 1 m<sup>2</sup> area each that are attached to the ceiling of the underground tunnel. Two triggers of the Carpet array and the proper MD trigger formed by the coincidence scheme upon the actuation of any three out of five MD modules are used to record information. The Carpet and MD operate independent of each other and have different dead times of recording electronics. But time markers of events in the MD and Carpet are produced by

one and the same clock, so that coincident events are reliably identified within a time interval  $\Delta t = 1$  ms. The total number of relativistic particles within the Carpet ( $N_{r.p.}$ ) and the number  $n_\mu$  of muons recorded by the MD are experimentally measured quantities used to determine the energy of EAS and the total number of muons in it, respectively. The events satisfying the following conditions are included into processing:

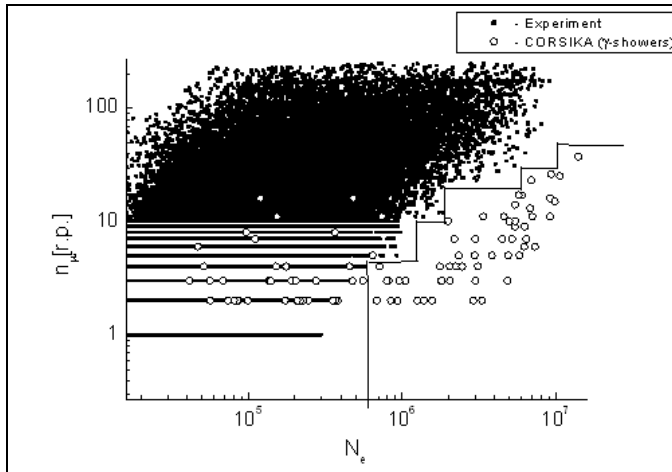
1. Shower axes are well within the “Carpet;”
2. Zenith angles of showers  $\theta < 40^\circ$ ;
3.  $N_{r.p.} \geq 2 \cdot 10^4$ ;
4. The number of nonzero detectors is more than 300.

After such a selection about  $1.3 \cdot 10^5$  showers survived from all showers detected during the period since 1999 to 2011. Net time of data accumulation is equal to 3390 days ( $\sim 9.2$  years). For modeling showers the CORSIKA code v.6720 was used (model QGSJET01C for higher energy and FLUKA 2006 for low energy) [13]. 5400 showers from primary protons and 6597 showers from primary iron nuclei were simulated within the energy interval (0.316–31.6) PeV, as well as 815 showers from primary gamma rays in the range (0.3–9) PeV. As a result of modeling, the following averaged relations were obtained:

- $E_p [GeV] = 174 \cdot N_e^{0.48}$ ;
- $E_\gamma [GeV] = 138 \cdot N_e^{0.65}$ .

### 3. The flux upper limits for diffuse cosmic gamma rays

In order to distinguish showers from primary gamma rays against the background ordinary showers, the analysis of correlated dependence in the  $n_\mu - N_e$  plane of detected and simulated events has been carried out (figure 2). In this work we analyze the region with  $N_e \geq 6 \cdot 10^5$ , in which one can separate the simulated gamma rays from ordinary EAS for the used method of processing experimental data.



**Figure 2.** Dependence  $n_\mu$  versus  $N_e$ .

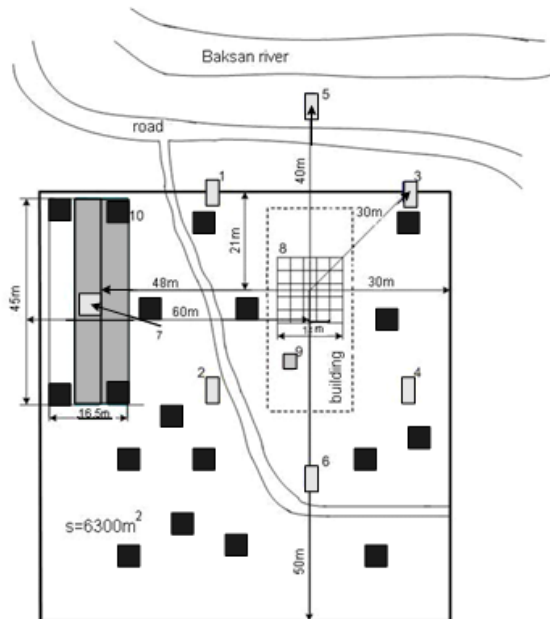
In order to evaluate the efficiency of selection of gamma rays at  $N_e \geq 6 \cdot 10^6$  on the plane  $n_\mu - N_e$  it is necessary to isolate the region where only simulated gamma-ray showers exist without any detected EAS. In figure 2 the boundary of this region is shown by a broken line. The ratio of the number of gamma-ray showers in this region to the total number at  $N_e \geq 6 \cdot 10^6$  is the detection efficiency  $\varepsilon_\gamma$ . The value of  $\varepsilon_\gamma$  for this interval of  $N_e$ , estimated in this way, is equal to 0.96. Since no detected events are present in this region (there is no background) one can use the following formula for estimation of the flux upper limit for primary gamma rays at the 90% confidence level:

$$I_{\gamma} = \frac{2.3}{S \cdot \Omega \cdot T \cdot \varepsilon_{\gamma}}, \quad (1)$$

where  $S = 200 \text{ m}^2$  is the area on which EAS axes are detected,  $T$  is the net time of data accumulation, and  $\varepsilon_{\gamma}$  is the detection efficiency for showers from primary gamma rays. Using the derived values of efficiency the upper limits for the flux of diffuse cosmic gamma rays with energies  $E_{\gamma} \geq 9.3 \cdot 10^{14} \text{ eV}$  ( $N_e \geq 3.1 \cdot 10^5$ ),  $E_{\gamma} \geq 1.4 \cdot 10^{15} \text{ eV}$  ( $N_e \geq 5 \cdot 10^5$ ),  $E_{\gamma} \geq 2.2 \cdot 10^{15} \text{ eV}$  ( $N_e \geq 7 \cdot 10^5$ ) were obtained. These fluxes are equal to  $I_{\gamma} = 4.0 \cdot 10^{-15} [\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}]$ ,  $I_{\gamma} = 5.1 \cdot 10^{-15} [\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}]$ , and  $I_{\gamma} = 3.8 \cdot 10^{-15} [\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}]$ , respectively. Shown in figure 5 are the limits on the integral flux of cosmic diffuse gamma rays versus the energy of primary photons. They are presented together with results of the other experiments.

#### 4. The Carpet-3 experiment

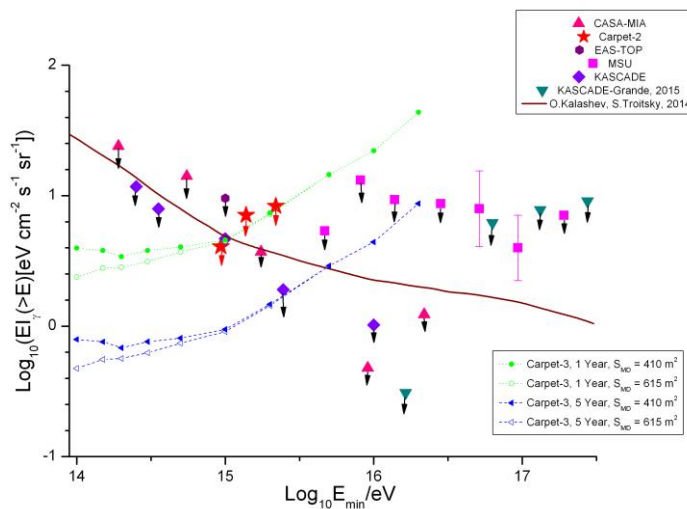
Realization of the experiment suggests that continuous area of MD should be increased at first up to  $410 \text{ m}^2$  and then up to  $615 \text{ m}^2$ . Also, 20 additional shower detectors will be installed to extend the array. Every such detector will contain 9 scintillation counters of  $1 \text{ m}^2$  area each (figure 3). At the present stage 410 scintillation counters with total continuous area  $410 \text{ m}^2$  are installed in the MD underground tunnels, and they are totally equipped with electronics. The work on adjusting the electronics of scintillation counters and on constructing data acquisition system for the given configuration of MD is in progress. The efficiency of selection of gamma ray showers and the array sensitivity to their detection are calculated for different configurations of the array. Figure 4 shows the expectation limits for flux of cosmic diffuse gamma rays for two configurations of the Carpet-3 air shower array and for two values of data accumulation time. As is seen, even at the MD area of  $410 \text{ m}^2$  the new array will have the best sensitivity to the flux of primary gamma rays with energies in the range  $100 \text{ TeV} - 1 \text{ PeV}$ .



**Figure 3.** Layout of the Carpet-3 air shower array: 1-7 are the outdoor huts with scintillators, 8 is the Carpet, 9 is the neutron monitor, and 10 is the muon detector. Black squares represent new modules with scintillation detectors.

## 5. Conclusion

The experiment aimed at searching for local sources of gamma rays with energy higher than 100 TeV was made with the Carpet air shower array of the Baksan Neutrino Observatory of INR of RAS in 1980s. A burst of gamma rays with energy  $E_\gamma \geq 100$  TeV [14] was detected from the Crab Nebula, while for the other probable sources of gamma-radiation only flux upper limits were obtained [15]. The new experiment is planned since the interest in search for diffuse primary gamma rays with energy higher than 100 TeV has increased recently due to results of the IceCube experiment, in which high-energy neutrinos of astrophysical origin were detected. It was shown in [16] that if such neutrinos are a result of decays of charged pions in the Galaxy, then neutral pions of the same energy should exist whose decays must produce considerable flux of gamma rays in the range of energies  $10^{14} - 5 \cdot 10^{17}$  eV. Predicted flux of cosmic diffuse gamma rays of galactic origin in this work is close to existing experimental limits in the range lower than about 5 PeV, and with improved sensitivity of Carpet-3 one can hope to detect it or at least to obtain the best upper limit.



**Figure 4.** Limits on the integral flux of gamma rays versus their energy.

## Acknowledgments

The work was supported by the Russian Foundation for Basic Research, project numbers 16-02-0687 and 16-29-13049.

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