The Carpet-3 EAS array to search for cosmic diffuse ultra-high energy gamma-rays

D.D. Dzhappuev[1], V.B. Petkov[1], A.S. Lidvansky[1], V.I. Volchenko[1], G.V. Volchenko[1], E.A. Gorbacheva[1], I.M. Dzaparova[1], A.U. Kudzhaev[1], N.F. Klimenko[1], A.N. Kurenya[1], O.I. Mikhailova[1], K.V. Ptitsyna[1], M.M. Khadzhiev[1], A.F. Yanin[1]

[1] Institute for Nuclear Research, Russian Academy of Sciences; Moscow, Russia;

dzhappuev@mail.ru

Abstract At the moment an experiment for measuring the flux of cosmic diffuse gamma rays with energy higher than 100 TeV (experiment Carpet-3) is being prepared at the Baksan Neutrino Observatory. The preparation of the experiment implies considerable enlargement of the area of both muon detector and surface part of the shower array. Sensitivity of the experiment to showers generated by primary gamma rays is estimated for different configurations of the future array. Also presented are the results of measurements made with a smaller area of the muon detector (the Carpet-2 experiment) for a net exposure of 9.2 years. Preliminary estimates of the upper limit on the flux of diffuse cosmic gamma rays with energies above 930 TeV are derived.

Keywords: Cosmic Rays, Extensive Air Showers, Primary Diffuse Gamma Rays, Muon-poor Showers

1. Introduction

To measure the flux and spectrum of diffuse primary cosmic gamma rays with energies higher than 100 TeV is of great interest for solving the problem of origin of cosmic rays, one of the most important in high energy astrophysics. As opposed to ordinary 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 (the more so) 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. For the first time this method was suggested in paper [1]. Since then, many experiments were carried out to search for gamma ray showers in a wide energy range. One can find reviews on these experiments in papers [2-5]. The experiments with air shower arrays at Mt. Chakaltaya, Tien Shan, Yakutsk and Lodz reported about some positive results for gamma rays in the energy range 10^{14}-$5x10^{17}$ eV. However, these results had low statistical significance and were not confirmed afterwards.

Later, high-energy primary gamma rays were searched for in the energy range 3×10^{14} – 5×10^{16} eV by the air shower arrays EAS-TOP, CASA-MIA, and KASCADE and at energies above 10^{18} eV by the arrays Haverah Park, AGASA, Yakutsk, Pierre Auger, and Telescope Array. All these experiments obtained only the upper limits on flux values, which appeared to be much lower than previously measured fluxes in early experiments.

Many years ago the experiment aimed at searching for local sources of gamma rays with energy higher then 100 TeV was made with the Carpet air shower array of the Baksan Neutrino Observatory of INR of RAS. A burst of gamma radiation with energy $E_\gamma \geq 100$ TeV was detected from the Crab Nebula [6], while for other possible sources of gamma rays the flux upper limits were obtained [7].

The interest to searching for primary gamma rays with energies higher than 100 TeV has recently greatly increased in connection with the results of the IceCube experiment, where high energy neutrinos of astrophysical origin were found. In [8] it was suggested that such neutrinos are a result of decays of charge pions in the Galaxy. If so, the neutral pions of the same energy should exist, whose decays produce a considerable flux of gamma rays in the energy range 10^{14} - $5\cdot10^{17}$ eV. The flux of diffuse galactic gamma rays predicted in this paper is close to available experimental limits in the energy range lower than approximately 5 PeV, and it can be detected in the Carpet-3 experiment. This project is a further development of the Carpet-2.

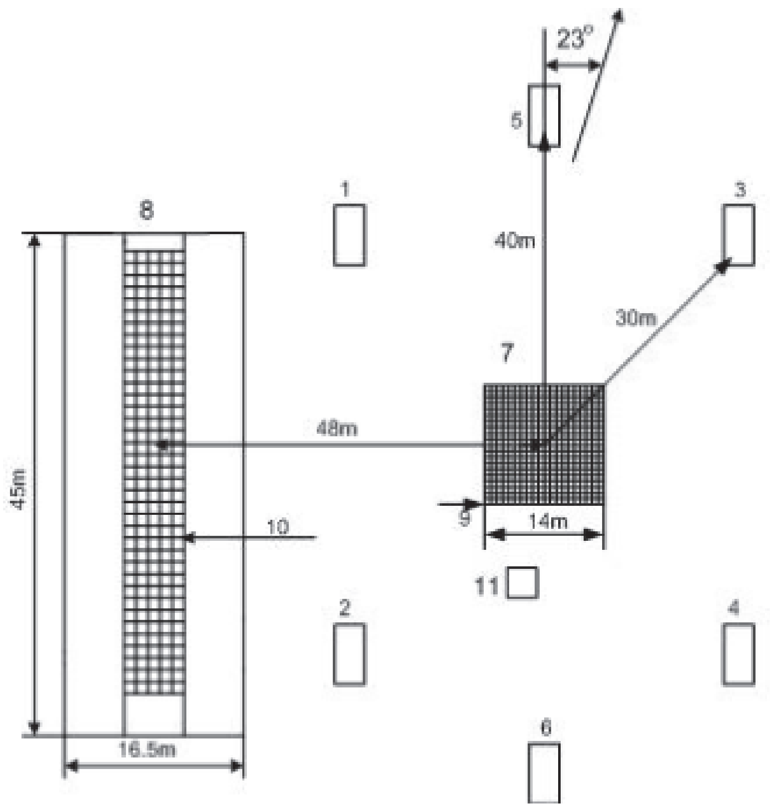

Fig1. *Layout of the Carpet-2 array detectors: 1-6 are huts with liquid scintillation detectors, 7 is the Carpet of liquid scintillators, 8 is the muon detector (MD), 10 are its plastic scintillators, and 11 is the neutron monitor. The arrow in the upper part of the figure shows the direction to the north.*

2. The Carpet-2 experiment

The Carpet-2 air shower array [9, 10] of the Baksan Neutrino Observatory is located at North Caucasus near Mt. Elbrus at an altitude of 1700 m above sea level (the atmospheric thickness is 840 g/cm^2 and geomagnetic cutoff rigidity is 5.6 GV). It consists (***Fig1***) of a surface part, the Carpet with six external huts (EH) and underground muon detector (MD). The distance between centers of the Carpet and MD is 48 m. The Carpet that detects the EAS electron-photon component includes 400 scintillation counters forming a square (20x20) with a total area of 196 m^2. Each EH contains 18 counters (9 m^2) of the same type as those in the Carpet. The muon detector records the muon component with energy threshold of 1 GeV. It has 175 plastic scintillation counters, each of area of 1 m^2. Anode pulses of PM tubes of these detectors are joined in groups of 35 to feed 5 analog summators. The summed signals come to inputs of charge-to-digital converters (CDC) whose threshold of actuation is 0.5 r.p. (1 r.p. or relativistic particle corresponds to the most probable energy release of a single particle in a detector, it equals 10 MeV for MD counters and 50 MeV counters of the Carpet and EH). Pulses from CDC are sent to input of the scheme of event selection (SES), which generates an output trigger signal when 2 or more pulses appear at its input. This signal permits data recording for a particular event in the MD data acquisition system. Signals of six EH are used to determine the shower arrival directions. For EAS having axes within the Carpet the accuracy of determining their coordinates is no worse than 0.7 m, while the angular accuracy of shower direction determination is about 3°. The Carpet and MD operate independently of each other, and their recording systems have different dead times. However, since time tags of events in the MD and Carpet are produced by one and the same clock, coincident events are reliably identified within the time interval $\Delta t = 1$ ms.

The total number of relativistic particles within the Carpet ($N_{r.p.}$) and the number n_μ of muons recorded by the MD are the 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 $\theta < 40°$;
3. the total energy release in the Carpet $N_{r.p.} \geq 10^4$.
4. the number of counters in the Carpet with signals exceeding 10 r.p. is ≥ 300.

After such a selection, the number of showers recorded in the period since 1999 to 2011 is equal to 1.3×10^5. The net exposure time for this period is 3390 days (≈ 9.2 years). The CORSIKA code v. 6720 (the QGSJET01C model for high energies FLUKA 2006 for low energies) [11] was used for modeling the showers. 5400 showers from primary protons 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 averaged energy dependence was obtained for N_e, and n_μ was determined as a function of E_0 and N_e.

3. Upper limit on diffuse flux of cosmic gamma rays

In order to distinguish the showers from primary gamma rays on the background of ordinary EAS, we have analyzed correlation dependences in the plane $n_\mu - N_e$ for detected and simulated events (***Fig2***). In this paper we consider the energy region $N_e \geq 6\times10^5$ where, with the used method of processing experimental data, one can separate simulated gamma-ray showers from ordinary EAS events.

To evaluate the efficiency of selection of gamma-ray showers at $N_e \geq 6\times10^5$, $N_e \geq 10^6$, and $Ne \geq 5\times10^6$ we isolated on the plane $n_\mu - N_e$ the area where only simulated gamma-ray showers are present, and there are no really detected showers. The boundary of this region is shown by a broken line in ***Fig2***.

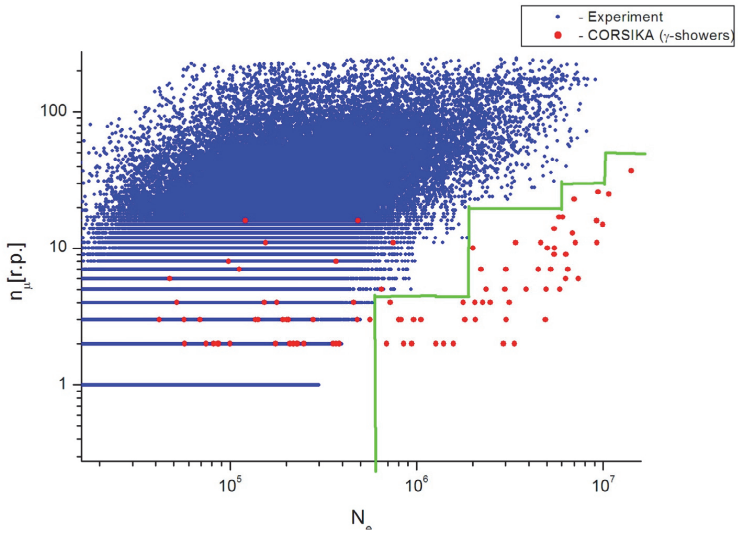

Fig2. *The n_μ versus N_e dependence: experiment and CORSIKA gammas.*

The ratio ε_γ of the number of simulated gamma-ray showers in a particular area to the total number is the efficiency of detection for this area. For three intervals $N_e \geq 6\times10^5$, $N_e \geq 10^6$, and $N_e \geq 5\times10^6$ the calculated values of ε_γ are equal to 0.95, 0.9, and 1.0, respectively. Based on the fact that there are no detected events in a specified region (no background, N_B=0), one can use the following formula for estimation of the flux of primary gamma rays at 90% confidence level:

$$I_\gamma = \frac{2.3}{S \cdot T \cdot \Omega \cdot \varepsilon_\gamma}$$

where S = 200 m^2 is the detection area for EAS axes, T is the net exposure (data taking) time, and ε_γ is the detection efficiency for showers from primary gamma-rays. Using the above derived values for efficiency, the upper limits were obtained for $E_\gamma \geq 9.3\times10^{14}$ eV, ($N_e \geq 6\times10^5$), $E_\gamma \geq 1.3\times10^{15}$ eV ($N_e \geq 10^6$), and $E_\gamma \geq 3.2\times10^{15}$ eV ($N_e \geq 5\times10^6$) (see ***Table1*** below).

Table1.

N_e	E_γ[eV]	N_B	ε_γ	log10(E_γ I_γ(>E)) [eV cm^{-1}sec^{-1} sr^{-1}]
$\geq 6\times10^5$	$\geq$ 9.3×10^{14}	0	0.95	0.61
$\geq 10^6$	$\geq$ 1.3×10^{15}	0	0.99	0.85
$\geq 5\times10^6$	$\geq$ 3.2×10^{15}	0	1.0	0.92

Fig3 presents the limits on the integral flux of cosmic diffuse gamma rays as a function of energy of primary photons together with the results of other experiments. It should be noted that our results present in this paper are preliminary, and the upper limits presented in ***Fig3*** and Table can be refined after more careful analysis of experimental data.

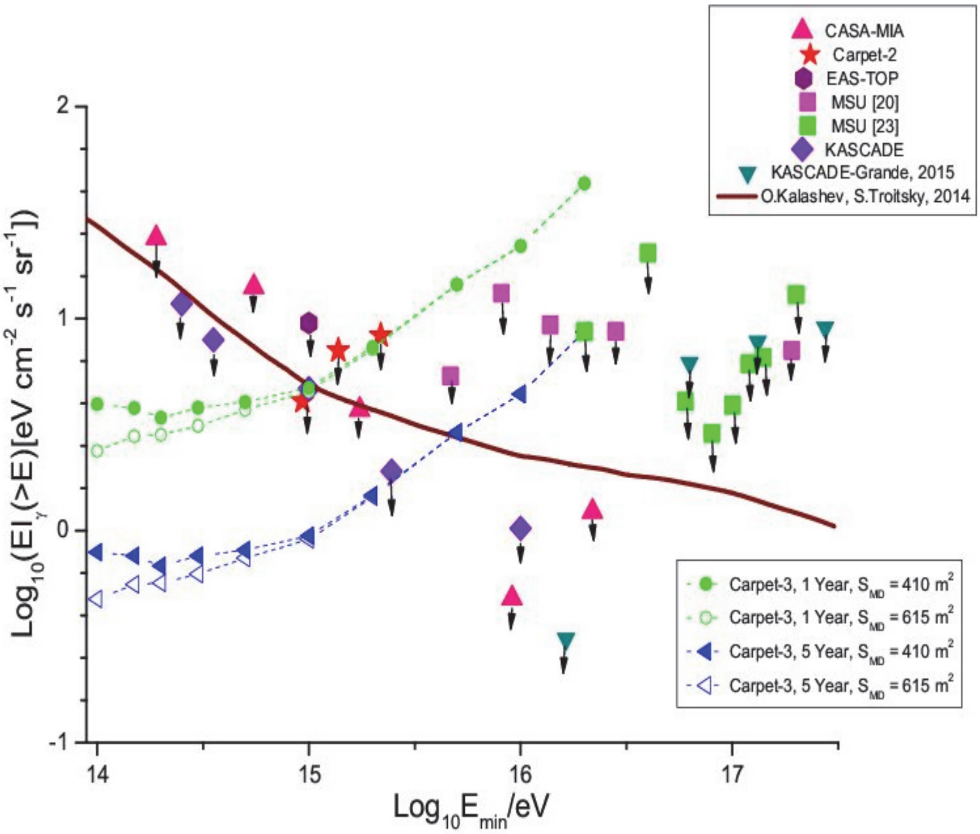

Fig*3.* *The Carpet-3 sensitivity to the flux of diffuse cosmic gamma rays.*

4. The Carpet-3 experiment

Preparation of the experiment suggests a step-by-step increase of the MD's continuous area: at first up to 410 m^2 and then up to 615 m^2. The area of EAS axes detection also will be increased. For this purpose 20 additional modules will be installed with 9 scintillation counters of area 1 m^2 each (see ***Fig4***).

At the moment 410 plastic scintillation counters with the total area of 410 m^2 are installed in the MD underground tunnels. They are fully equipped with necessary electronic circuits. Also the work on adjustment of these counters and on creation of the special data acquisition system for a new configuration of the MD is in progress.

At the same time, calculations have been carried out to estimate the efficiency of selection of gamma rays and the sensitivity of different configurations of the new array to air showers initiated by primary gamma rays. ***Fig3*** demonstrates the expected limits on the flux of diffuse cosmic gamma rays for two configurations of the Carpet-3 array and for two periods of data accumulation. One can see that even at the MD area equal to 410 m^2 the new array will have the world-best sensitivity to the flux of cosmic gamma rays with energies in the range 100 TeV – 1 PeV.

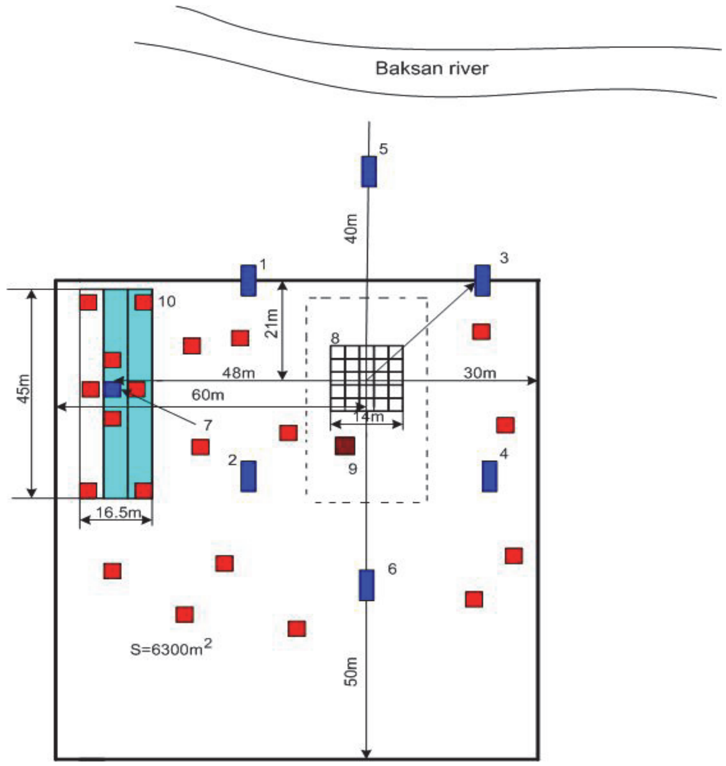

Fig4. *The layout of the Carpet-3 air shower array. The big blue rectangle shows the MD area filled with plastic scintillation counters. The dark blue and red patches present outdoor huts (modules) with scintillation detectors.*

5. Conclusions

1. From the results of the Carpet-2 air shower array the upper limits on the flux of diffuse cosmic gamma rays with energy above 900 TeV are derived.
2. In order to provide for efficient detection of air showers initiated by gamma rays with energies higher than 100 TeV, it is necessary to perform the array modernization with a considerable increase of the Muon Detector area (The Carpet-3 experiment).
3. In this case, several years of data accumulation will make it possible to improve significantly the results currently available on measuring the 100 TeV flux of cosmic diffuse gamma rays.
4. This work is now in progress.

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