Limits on the isotropic diffuse gamma-ray flux between 100 TeV and 1 PeV: experiments Carpet-2 and Carpet-3

V.S. Romanenko[1*], V.B. Petkov[1,2], D.D. Dzhappuev[1], A.S. Lidvansky[1], E.A. Gorbacheva[1], I.M. Dzaparova[1,2], 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 of RAS, Moscow, Russia; vsrom94@gmail.com*

[2]*Institute of Astronomy of RAS, Moscow, Russia*

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 implies the extension of the existing Carpet air shower array by increasing areas of both muon detector and surface scintillation detectors. In this paper we present estimates of sensitivity of the experiment to showers from primary gamma-rays for different configurations of the accomplished array. Using experimental data of the previous version of the array (Carpet-2) accumulated for 9.2 years, preliminary estimates of the flux upper limit is deduced for cosmic gamma-rays with energies above 700 TeV.

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

1. Introduction

Search for gamma-rays with energies higher than 100 TeV is applied in the Extensive Air Shower (EAS) method, which has been used since 1960 [1]. EAS is generated by the primary cosmic rays that strike the atmosphere and produce many secondary particles. Opposed to primary protons and other charged cosmic rays, which deflecte 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 density of cosmic rays in the interstellar space.

Investigation of diffuse gamma rays at such energies by the EAS method is based on separation of the showers from primary gamma-rays and other charged particle (protons and nuclei). Because the number of muons in gamma showers is lower than that in proton showers, and if one selects muon-poor EAS, theoretically, it is possible to separate the showers initiated by primary gamma rays with reliable efficiency.

Many experiments have been carried out to search for gamma showers in a wide energy range, a review of which is given in [2, 3, 4, 5]. The experiments at Mt Chacaltaya, Tien Shan and Yakutsk are worked on this principle and announced the registration of gamma showers in the range $10^{14} - 5\times10^{17}$ eV. But they had insufficient statistical significance and were not confirmed later. More careful subsequent experiments (collaborations EAS-TOP, and KASCADE in the energy range $3\times10^{14} - 5\times10^{16}$ eV, and Haverah Park, Yakutsk at energies higher than 10^{18} eV) yielded only upper limits on the fluxes of cosmic gamma rays. Those limits appeared to be much lower than the fluxes of diffuse cosmic gamma rays supposedly measured in earlier works. In the MSU experiment the search for showers from primary gamma rays in an energy range of $5\times10^{15} - 2\times10^{17}$ eV, conducted by the method of selection of muonless showers, also yielded only upper limits with an exception of the region $5\times10^{16} - 10^{17}$ 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 [6] 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. However, the full-scale reanalysis of the MSU data with modern simulations of the installation does not confirm previous indications of the excess of gamma-ray candidate events. So, the final results of the MSU experiment are also only upper limits on the flux of diffuse gamma rays in the energy range of $\sim (10^{16} - 10^{17.5})$ eV [7, 8].

2. The Carpet-2 experiment

The Carpet-2 air shower array [9, 10] 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^2) (Fig. 1).

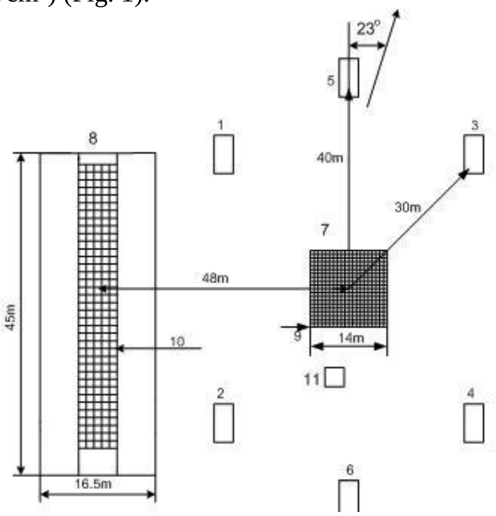

***Fig1**. The layout of the Carpet-2 multipurpose air shower array: 1-6 are outdoor huts with scintillators, 7 is the Carpet, 8 is the muon detector, and 9 is a neutron monitor.*

The array consists of a ground level detector called the Carpet (200 m^2), six outdoor huts with 9 m^2 of scintillation detectors in each, an underground muon detector and a neutron monitor. The Carpet consists of 400 liquid scintillation detectors; each has an area of 0.5 m^2. 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 shape of 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: dX = dY = 0.35 m, $dN_e/N_e = 0.1$ in the EAS size interval $N_e = 10^5 - 5\times10^6$.

The muon detector (MD) is located in an underground tunnel at a depth of 500 g/cm, which corresponds to the energy threshold of 1 GeV. The distance between its center and the center of the Carpet is equal to 48 m. The MD is an array of size 5×35 m, and it consists of 175 plastic scintillation counters of 1 m^2 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 are operating 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 the time interval dt = 1ms. The total number of relativistic particles within the Carpet ($N_{r.p.}$) and the number n_μ 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:

- shower axes are inside the Carpet (effective area ~160 m^2);
- zenith angles of showers $\theta < 40°$;
- the total energy release in the Carpet ≥ 10^4 r.p.;
- the number of fired counters in the Carpet ≥ 300.

After such a selection, the number of showers recorded in a period from 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.

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_μ – N_{ch} for detected and simulated events (Fig. 2). In this paper, we consider the energy region $N_{ch} \geq 3.5\times10^5$ where by using methods of experimental data processing, one can separate simulated gamma-ray showers from ordinary EAS events.

To evaluate the efficiency of selection of gamma-ray showers we isolated on the plane n_μ – N_{ch} the area where only simulated gamma-ray showers are present, and in reality, there are no of detected showers. A red line in Fig. 2 shows the boundary of this region.

We can use the following formula for the estimation of the flux upper limit for primary gamma rays:

$$I_\gamma = \frac{N_{90}}{S \cdot T \cdot \Omega \cdot \varepsilon_1 \cdot \varepsilon_2}. \quad (1)$$

Because no experimental events below the red line N_{90} is equal to 2.3, it may be evaluated from Poisson statistics at a 90% confidence level. S is the efficient area of the Carpet without counters placed at the perimeter (~160 m^2), T is the net exposure (data acquisition) time, ε_1 is the trigger and reconstruction efficiency of events, and ε_2 is the selection efficiency for gamma showers which is given by $\varepsilon_2 = N_{select}(\geq E)/N_{total}(\geq E)$.

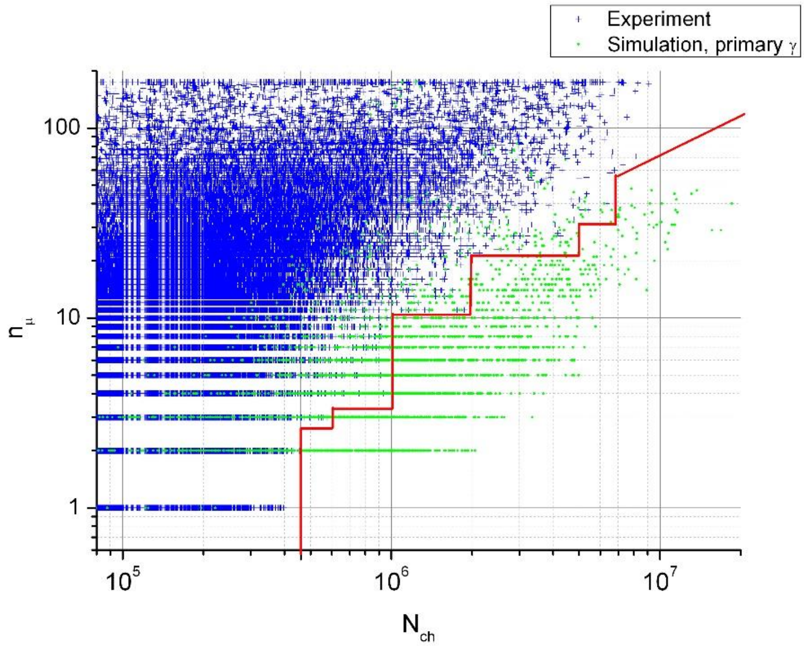

Fig. 2. *The n_μ versus N_{ch} dependence. The blue dots correspond to experimental events, the green dots are simulated gamma-rays showers and the red line is the boundary of selected region.*

Fig. 3 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 presented in this paper are preliminary, and the upper limits presented in Fig. 3 can be refined after more careful analysis of experimental data.

4. The Carpet-3 experiment

Preparation of the experiment suggests a systematic 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 will be also increased. For this purpose, 20 additional modules will be installed with 9 scintillation counters of area 1 m^2 each (see Fig. 4).

At the moment 410 plastic scintillation counters with a total area of 410 m^2 are installed in the MD underground tunnels. They are fully equipped with necessary electronic circuits. 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. Figure 3 also 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.

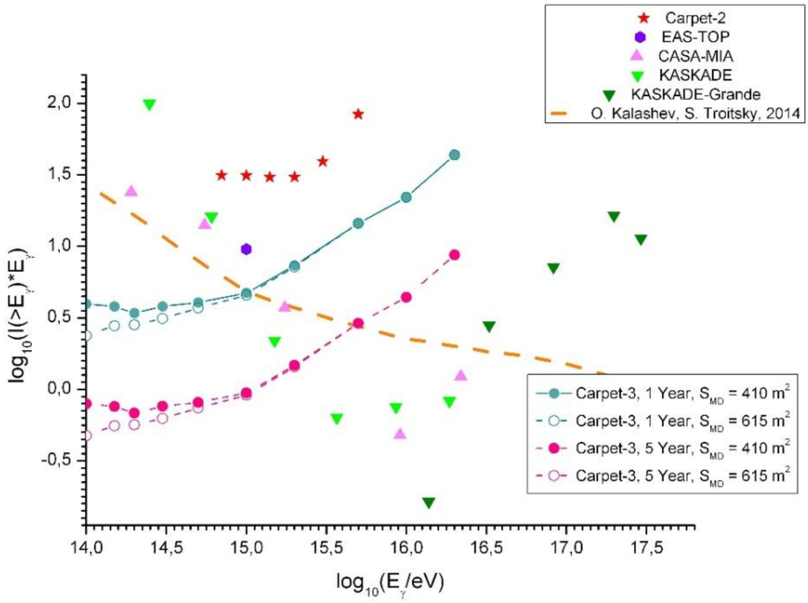

Fig3. *Limits on the integral flux of gamma rays versus their energy and sensitivity of the Carpet-3 air shower array.*

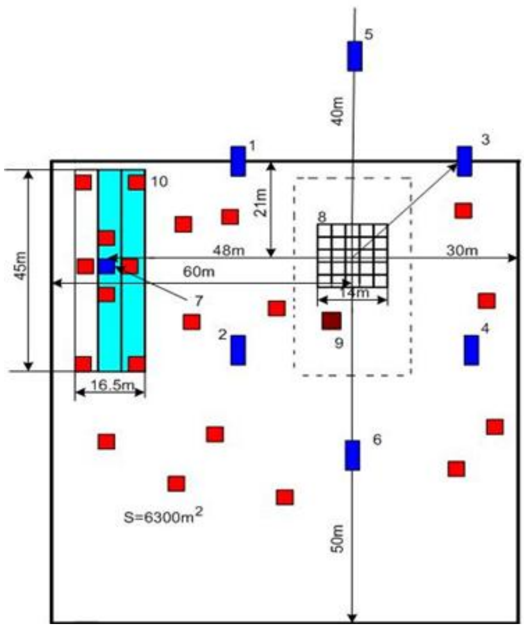

Fig4. *The layout of the Carpet-3 air shower array. The big blue rectangle shows the MD area filled with plastic scintillation counters. The dark blue and red patches present outdoor huts (modules) with scintillation detectors.*

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 were 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. The Carpet-3 air shower array is under construction at the Baksan Neutrino Observatory by step-by-step upgrade and extension After final accomplishment of this array it can be competitive in its class and will have a chance to get the world-best limit on the flux of gamma rays of cosmic origin.

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