The Carpet-3 multipurpose shower array for searching cosmic diffuse gamma rays with energy $E_\gamma > 100$ TeV

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Abstract. An experiment for measuring the flux of cosmic gamma rays with energy above 100 TeV is currently being prepared at the Baksan Neutrino Observatory of the Institute for Nuclear Research, Russian Academy of Sciences. At present the plastic scintillation counters with a total continuous area of 410 m$^2$ are installed in the muon detector (MD) underground tunnels, and they are totally equipped with electronics. Six modules of shower detectors have been already placed on the surface of the MD absorber. In each of them 9 standard plastic scintillation counters are placed with an area of 1 m$^2$ each. These modules are components of the ground surface part of Carpet-3 shower array. The data acquisition system for this array is almost ready. Expected flux limits for 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 this flux or at least to obtain the best upper limit.

1. Introduction

Interest in searching for primary gamma rays with energy above 100 TeV noticeably increased in recent times in connection with the results of the IceCube experiment in which high-energy neutrinos of astrophysical origin were detected. It was shown in [1] that if these neutrinos are a result of decays of charged pions in the Galaxy, there also must exist neutral pions having the same energy range from $10^{14}$ to $5 \cdot 10^{15}$ eV during their decay. Diffuse gamma rays at energies $E_\gamma > 100$ TeV are searched for by the EAS method in experiments in which one can separate the showers produced by primary photons and nuclei. This separation is possible due to the fact that showers from primary photons are significantly depleted in hadrons (and, as a consequence, in muons) as compared to showers from primary nuclei. The Carpet-3 multipurpose shower array developed at the Baksan Neutrino Observatory, Institute for Nuclear Research, Russian Academy of Sciences, already has a muon detector with an area of 410 m$^2$, with the possibility to increase its area to 615 m$^2$. To increase the detection area of EAS axes, ground base modules of scintillation counters will be additionally mounted. Preliminary estimates show that the new array will have the best sensitivity to the flux of primary gamma rays with energies in the range from 100 TeV to 1 PeV.

2. The Carpet-2 array

The Carpet-2 multipurpose shower array is intended for studying the electron, muon, and hadron shower components [2]. It is deployed at an altitude of 1700 m above sea level (depth of 840 g/cm$^2$ in the Earth’s atmosphere). Its coordinates are 43°25’N and 42°40’E, the respective vertical cutoff rigidity being 5.6 GV. The Carpet-2 array consists of a central part (Carpet) containing 400 liquid scintillator detectors 0.7×0.7×0.3 m$^3$ in size each, arranged in the form of a continuous square with a side of 14 m and total...
area of 196 m$^2$. The measured range of energy release values in an individual liquid detector of the Carpet is 10-5000 relativistic particles (r.p.), where 1 r.p. is the most probable value of the energy released by a single muon ($\varepsilon \sim 50$ MeV) that traversed a liquid detector in a vertical direction. Six outer stations intended for determining shower arrival direction are arranged about the central part of the array. Four of them are positioned at a distance of 30 m and form a square; the remaining two are placed at a distance of 40 m from the geometric center of the Carpet. Each outer station has dimensions of 2.1×4.2 m$^2$ and contains 18 liquid scintillation detectors similar to those used in the Carpet. The data sampling is performed on the array by triggers M1 and M2. Trigger M1 is generated when pulses from four outer stations located 30 m from the Carpet center coincide with a pulse from the energy release in the Carpet. This trigger selects showers from primary particles with energies $E_o > 10^{14}$ eV. The frequency of such events is ~1.2 Hz. Trigger M2 is generated by a signal from the energy release in the Carpet with a threshold of 2.5 GeV. A muon detector (MD) is arranged at a distance of 48 m from the central part of the array; it is placed in an underground tunnel at a depth of 500 g/cm$^2$, which corresponds to the energy threshold of 1 GeV.

3. The muon detector
The muon detector is an extended plane with dimensions of 5×35 m$^2$ and consists of 175 standard plastic scintillation counters with an area of 1 m$^2$ each. The counters are attached to the ceiling of the underground hall. Each counter comprises four plastic scintillators with dimensions of 0.5×0.5×0.05 m$^3$ in a light-proof casing. The plastic scintillators are viewed by FEU-49 photomultiplier tube (PM) with 12 dynodes. Anode signals of the PM are summated in groups and form five modules with 35 detectors in each group. A signal from the 12th dynode is reshaped by a RC logarithmic converter with a threshold of 0.5 r.p. into a standard variable-duration signal delivered to the hodoscope of the amplitude channels. The RC converter is a logarithmic encoder whose operating principle is based on charging the capacitance C with a pulsed current from the PM and its exponential discharge through a resistor $R$. The conversion time constant is 1µs. The filling of a convertor signal with 10-MHz frequency pulses ensures a 10% measurement accuracy. The measurement range of the energy release of the convertor is from 6 to 20000 MeV. Information from the counters is recorded using two triggers of the Carpet array and the intrinsic MD trigger generated by the coincidence circuit upon the actuation of any three of five MD modules.

4. The Carpet-3 array
The Carpet-3 shower array (figure 1) is designed based on the existing Carpet -2 array [3-4].

![Figure 1. Carpet-3 multipurpose air shower array: (1-6) are old outdoor stations with scintillators, 8 is Carpet, 9 is neutron monitor, and 10 is muon detector. Red squares represent the new modules with scintillation detectors.](image)
Preparations for this experiment entail a gradual increase in the continuous area of the muon detector (MD), first to 410 m$^2$ and then up to 615 m$^2$. At the same time, to increase the detection area of the EAS axes, 20 additional modules with liquid scintillation counters in each module will be installed. The area of each counter is equal to 0.5 m$^2$. At the moment, 410 scintillation counters with a total continuous area of 410 m$^2$ have already been installed in the MD underground tunnels. They are fully equipped with electronics. The testing of the scintillation counter electronics is under way, and the data acquisition system for the MD configuration is being designed. Seven modules with heat insulated walls have been already mounted on the surface of the muon detector absorber. The thermal control for the module detectors will be implemented by heating them from below using flexible tape heating elements (FTHEs). The detectors will be mounted in three rows in each detector; under each of them, three heating tapes with a power of 200 W each will be placed. The total power of the heating elements for a module will be 1.8 kW. The electric circuit of the thermostat will ensure stabilization of the detector temperature at a level of ± 0.25°C during the whole year, which will stabilize the signal from the detectors at a level of 0.1%. The views of the first tunnel of MD and a module with the plastic detectors are presented in figure 2, and at in figure 3, respectively.

5. The preliminary results for diffuse gamma radiation

For evaluation of the efficiency of gamma ray selection artificial showers were simulated with the help of CORSIKA code v.6720 (model QGSJET01C for high energy and Fluka 2006 for low energy) [5]. 5400 showers from primary protons within energy range (0.316-31.6) PeV were simulated, as well as 815 events of primary gamma-rays in the energy range (0.3-9) PeV. As a result of simulation made for showers from primary protons and gamma rays, the following dependencies have been obtained: $N_\gamma(E_\gamma)$, $n_\mu(E_\gamma)$, and $n_\mu(N_\gamma)$. Hence, the efficiency of shower detection with reconstructed $N_\gamma$ is derived. In order to distinguish gamma-initiated showers from the background ordinary showers the analysis of detected and simulated events in the $n_\mu-N_\gamma$ plane was performed (figure 4). In this paper we analyze the region with $N_\gamma \geq 6 \times 10^3$, in which one can separate the simulated gamma ray showers from ordinary EAS at the used method of processing experimental data. In order to evaluate the efficiency of selection of gamma rays at $N_\gamma \geq 6 \times 10^3$ on the plane $n_\mu-N_\gamma$ it is necessary to isolate the region where only simulated gamma rays showers exist without any points of detected EAS. In figure 4 the boundary of this region is shown by a broken line.
Figure 4. The $n_\mu - N_e$ scatter plot for detected and simulated showers.

Since there are no detected events in the selected region (background is absent), one can use the next formula for estimation of the flux upper limit for primary gamma rays at 90% confidence level:

$$I_\gamma = \frac{N_{90}}{S \cdot \Omega \cdot T \cdot e_1 \cdot e_2},$$

where $N_{90} = 2.3$, $S \cdot \Omega \cdot T = 6.2 \times 10^{14}$ cm$^2$·sr·s, $e_1$ is the efficiency of shower detection with a given trigger and reconstructed shower parameters, $e_2$ is the efficiency of selection of showers from primary gamma rays, $e_2 = N_{\text{select}}(\geq E) / N_{\text{total}}(\geq E)$.

In our previous experiment (Carpet-2) the limits on integral flux (figure 5, red stars) of cosmic diffuse gamma radiation have been obtained as a function of energy of primary photons.

Figure 5. Upper limits on the integral flux of primary gamma rays versus the energy of gamma rays.

These results are compared with the results of other air shower arrays. The energy range for these fluxes is (0.5-5) PeV. Also presented in figure 5 are the expected limits on the flux of cosmic diffuse gamma radiation for two configuration of “Carpet-3” array and for two values of data accumulation time. As is seen, even with the MD area of 410 m$^2$ the new array will have the best sensitivity to the flux of primary gamma rays with energies in the range 100 TeV – 1 PeV.
6. Conclusion
At present the “Carpet-3” multipurpose shower array is developed at the Baksan Neutrino Observatory, Institute for Nuclear Research, Russian Academy of Sciences, already has a muon detector with an area of 410 m², with the possibility to increase its area to 615 m². The additional modules with liquid scintillation counters in each module will be installed. These modules are to increase the detection area of the shower axes and, consequently will make it possible to increase the statistics of recorded events and to decrease the energy threshold of the primary cosmic radiation.

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