Carpet-3 experiment for ultrahigh-energy astrophysics: Current-state and prospects

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Abstract. The Carpet-3 air shower array is being built at the Baksan Neutrino Observatory, which is located near Mount Elbrus (North Caucasus) at an altitude of 1700 m above sea level. The main aim of the experiment is gamma-ray astronomy in the energy range above 100 TeV to search for diffuse gamma radiation and sources and to study the generation mechanisms of this radiation. The paper provides an overview of the current state of the experiment, as well as its prospects.

1. Introduction

The measurement of the flux and spectrum of gamma-rays of cosmic origin with energies above 100 TeV is of great interest in solving the problem of the origin of cosmic rays. Unlike charged cosmic rays (protons and nuclei), which are deflected in interstellar magnetic fields, primary gamma radiation provides information on the spatial distribution and characteristics of cosmic-ray acceleration places. Cosmic radiation of ultrahigh-energy produces cascades of secondary particles in interactions with the atmosphere, which are called extensive air showers (EAS). An experimental search for primary gamma rays can be based on the separation of showers caused by primary photons from showers caused by protons and nuclei. Such a separation is possible because showers from primary photons are hadron-poor (and, as a consequence, muon-poor too), as compared with the showers from primary protons and nuclei. For the first time, the possibility of shower separation by the muon-poor method was proposed in [1]. Since then, many experiments tried to use this method in order to search for gamma-ray showers in a wide energy-range. Experiments on Mount Chacaltaya [2], Tien Shan [3], Lodz [4], made announcements about the registration of gamma-ray showers in the energy range $10^{14}$ to $5 \times 10^{17}$ eV. However, these results had low statistical significance and subsequently were not confirmed. Experiments on the top of the underground Gran Sasso laboratory (EAS-TOP) [5], Chicago EAS array [6] and Karlsruhe shower core and array detector (KASCADE) [7] searched for primary gamma-rays in the energy range $3 \times 10^{14}$ to $5 \times 10^{16}$ eV, while Haverah Park [8], Akeno EAS array [9], Yakutsk [10], Moscow State University EAS array [11] and KASCADE-Grande [12] operated for energies...
above $10^{18}$ eV. They obtained only the upper limits on the fluxes, which were lower than the fluxes of diffuse gamma radiation, registered in earlier works [2–4].

The IceCube experiment boosted interest in the search for primary gamma radiation with energies above 100 TeV due to the registration of high-energy neutrinos of astrophysical origin [13]. In [14] it was shown that, if such neutrinos are the result of decays of charged pions in the Galaxy, neutral pions of the same energies should exist. Their decays produce an additional gamma-ray flux in the energy range $10^{14}$ to $5 \times 10^{17}$ eV. Therefore, new installations with large-area muon detectors started to be created for the registration of gamma-ray showers. One can recall in the Tunka valley [15] in Russia, large high-altitude air-shower observatory [16] in China, array in the Andes [17]. Also working installations, such as EAS array at Ooty in India [18] and Tibet AS$\gamma$ [19] in China should be mentioned. The last team has got recently interesting results. In [20] they announced about the first in the world registration of gamma-rays from an astrophysical source (in particular, the Crab Nebula), at energies above 100 TeV with the statistical significance of 5.6 $\sigma$. However, previously a gamma-ray burst at such energies was detected from the Crab Nebula [21] at the Baksan Neutrino Observatory. Also, a signal from the Crab Nebula was detected by the high altitude water Cherenkov (HAWC) observatory [22] almost simultaneously with Tibet AS$\gamma$.

Due to the high relevance, the modernization is carried out on the Carpet-2 installation (the Carpet-3 experiment). The main aim of the Carpet-3 experiment is to search for ultrahigh-energy diffuse gamma rays, as well as to search for sources and their generation mechanisms. It will have a high sensitivity to the fluxes of cosmic gamma radiation accompanying the fluxes of astrophysical neutrinos of ultrahigh energies registered in the IceCube experiment.

2. Preceding results
The Baksan air shower array (BASA) for ultrahigh-energy gamma-ray astronomy [23] was among the first to make a start of the purposeful observations. The Carpet array consists of 200 m$^2$ big square detector with 400 scintillators in the center and six detectors, each of 9 m$^2$ area with 18 scintillators, see figure 1. Four are located at 30 m distance and two are at 40 m distance from the array center. Also, the Carpet array separated on the 25 units with 16 scintillators in each. All those detectors use the standard liquid scintillator counters of 0.5 m$^2$ area and 30 cm thickness.

Among all results of the BASA, the brightest were a possible burst in Cygnus X-3, associated with a radio burst, and a possible burst in the Crab Nebula, detected with different significance by several EAS arrays. The first event had happened in October 1985.

The intensity increase was concentrated during three days, October 14–16, 1985 [24,25]. The most interesting event occurred on February 23, 1989. An ultrahigh-energy gamma-ray burst was observed from the Crab Nebula direction [21]. Other experiments with different statistical significance confirmed this result. The EAS array at Kolar Gold Fields (India) reported on the detection of a burst at PeV energy from the Crab Nebula direction on the same day with Baksan EAS [26]. In [27] an additional comparison was made and analysis of simultaneous detection of the Crab Neala burst for Baksan and Kolar Gold Fields arrays were presented. EAS-TOP (Gran-Sasso, Italy) also observed the burst with lower significance, in [28] they present and discuss observation from the statistical point of view. In [29] the upper limits on the fluxes were presented for three possible point sources with a different period for the observation made by the Baksan group: Cygnus X-3 (1984–1989), Crab Nebula (1985–1989) and Hercules X-1 (1986–1989).

Subsequently, the BASA was updated and got the name Carpet-2. It included the Carpet array and a large-area muon detector (MD). Originally [30], the MD was planned to consist of 3 underground (500 g/cm$^2$ depth) tunnels with liquid scintillation counters of 30 cm thickness. Ultimately, the muon detector was constructed [31] with three parallel underground tunnels,
Figure 1. General view of the current state of Baksan EAS array. The Carpet array is used for the localization of the shower core. Six detectors around Carpet array are used for reconstruction of arrival direction and energy deposition. Underground muon detector is used for estimating the muon number in the shower. Additional ground detectors will be used for better sensitivity to showers of lower energy (up to 10 TeV in the final configuration). Seven detectors are fully ready to operate (green boxes) and the remaining (yellow boxes) will be installed during 2020.

but only one central tunnel was equipped with 175 (5 × 35) plastic scintillation counters with an area 1 m² each (the scintillator thickness is 5 cm), attached to the ceiling of the tunnel. The rock absorber above detectors is equal to 500 g/cm², which corresponds to the threshold energy for vertical muons 1 GeV. The distance between the centers of the Carpet and MD is equal to 47 m. Also, a method for separation of muons and hadrons is developed for the muon detector of the Carpet shower array. The use of this method allows one to measure hadron and muon components of EAS simultaneously. It made possible to separate EAS induced by primary gamma from proton EAS. As a result, the upper limit on the isotropic flux of diffuse gamma-rays with energy above 700 TeV was obtained [32]. It is derived from experimental data of the Carpet-2 array for the net exposure of 9.2 years of observation or 3390 days (during the period from 1999 to 2011).
3. The Carpet-3 EAS array

Carpet-3 EAS array [33] is the upgrade of the Carpet-2 facility. The main aim is to search for diffuse gamma-rays with better sensitivity. Furthermore, we are still interested in searching for point sources and will keep observation in our part of the sky.

Figure 1 shows the current installation status. The plan of the upgrade includes expanding the muon detector, creating additional ground-based shower detectors and upgrading the data acquisition system. Also, a detailed Monte-Carlo simulation is performed for the new configuration of the installation.

3.1. Surface array

We began to expand the surface array in order to improve both the angular resolution of the installation and its possibility of localizing the core of the shower over a larger area. Moreover, in the final stage, the array should have a better sensitivity to showers of lower energies. It will be efficient in the energy range of primary particles starting from 10 TeV (preliminary estimation). The surface array will consist of 33 new detectors. As shown in figure 1, seven detectors are ready to operate, while the remaining ones will be installed during 2020. Each detector has a 9 m$^2$ area and includes nine plastic scintillation counters whose analog signals are summed. The block diagram of the Carpet-3 EAS array data acquisition system is shown in figure 2.

**Figure 2.** The block diagram of the Carpet-3 EAS array (TDM—time division multiplexer).
Figure 3. The block diagram of the muon detector (LCM—large core memory).

For the EAS trigger signals from the constant-fraction discriminator (CFD) are used. The module generates a logic signal of a fixed duration. Its leading-edge coincides in time with the leading-edge of analog pulse caused by the passage of particles through the detector. The trigger condition is the coincidence of signals from (within a microsecond): first, the sum of all Carpet detectors with a threshold of 15 relativistic particles (r.p.), where r.p. is the most probable energy release in the detector from a charged particle having passed through the detector; second, 4 ground detectors now, and in the future, their number will be optimized by simulation results for better efficiency of EAS registration. Also, signals from the CFD are sent to the time-to-digital converter (TDC) to measure the arrival time of the event. The analog signal comes to the analog-to-digital converter (ADC) for the calculation of energy release in the detector.

3.2. Large area muon detector

We have increased the area of the muon detector up to 410 m² (compare to 175 m² in the Carpet-2), and now it completely fills two tunnels with standard plastic scintillation counters of an area of 1 m² each. Consequently, each tunnel is equipped with 205 counters (5 × 41).

The block diagram of the muon detector data acquisition system is presented in figure 3. 235 counters are equipped with the new electronics other 175 counters are equipped with old electronics (MD of the Carpet-2 EAS array). We use a standard shower trigger for the data
acquisition system of the MD. New counters are using the CFD and the logarithmic converter of charge to number-pulse code (LCCNPC). The LCCNPC module converts charge of an analog signal into a sequence of logical pulses, where the charge is proportional to the logarithm of the number of the logical pulses. These signals come to the counters of logic pulses in the online computer of the muon detector that allows one to measure the energy release in each detector. The CFD of the MD has the same operating principle as for surface detectors. Their signals are sent to TDC for taking information about the arrival time of the event. Old counters are using the logarithmic resistor-capacitor (RC) module that converts charge of the analog pulse to a logic signal of variable duration, where the charge is proportional to its duration. These signals are fed to the TDC for the duration measurements.

4. Conclusions
Thus, to effectively detect air showers initiated by gamma rays with energies above 10 TeV, it is necessary to perform the array modernization with a considerable increase of the muon detector area (The Carpet-3 experiment). In this case, several years of data accumulation will make it possible to improve significantly the results currently available on measuring the flux of cosmic diffuse gamma rays.

The Carpet-3 air shower array is under construction at the Baksan Neutrino Observatory by step-by-step upgrade and extension. After the 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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