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ELEMENTARY PARTICLES AND FIELDS
Experiment

Precision Measurements of High-Energy Cosmic Gamma-Ray Emission with the GAMMA-400 Gamma-Ray Telescope

A. M. Galper[1),2)], S. I. Suchkov[1)*], N. P. Topchiev[1)], I. V. Arkhangelskaja[2)], A. I. Arkhangelskiy[2)], A. V. Bakaldin[3)], Yu. V. Gusakov[1)], O. D. Dalkarov[1)], A. E. Egorov[1)], V. G. Zverev[1)], V. V. Kadilin[2)], A. A. Leonov[1),2)], P. Yu. Naumov[2)], M. F. Runtso[2)], M. D. Kheymits[2)], and Yu. T. Yurkin[2)]

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Abstract—The GAMMA-400 γ-ray telescope installed at the Russian space observatory is intended for precision measurements in the energy range of 20 MeV–1000 GeV of γ-ray emission (with the angular and energy resolutions several times better than that of current γ-ray telescopes) from discrete sources; measurement of the energy spectra of Galactic and extragalactic diffuse γ-ray emission; studies of γ-ray emission from the active Sun; and measurements of fluxes of γ-ray emission and electron–positron cosmic-ray component, which are probably associated with the annihilation or decay of dark-matter particles.

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INTRODUCTION

In accordance with the Federal Space Programs of Russia for 2009–2015 and 2016–2025, the activities are continuing at present to create the GAMMA-400 γ-ray telescope (gamma-astronomical multi-functional modular apparatus) [1, 2].

GAMMA-400, which will be installed at the Russian space observatory, is intended for studying γ-ray emission in the energy range of 20 MeV–1000 GeV, obtaining data for solving the problem of the nature of dark matter in the Universe, and developing the theory of the origin of high-energy cosmic rays.

GAMMA-400 will provide information about (i) the features in the energy spectra of high-energy γ-ray emission from discrete and extended sources and the electron–positron component that can be associated with dark-matter particles; (ii) the variability of high-energy γ-ray emission from discrete sources in order to clarify the nature of processes involving the acceleration of elementary particles in these sources; (iii) diffuse Galactic and extragalactic γ-ray emission; and (iv) high-energy γ-ray emission arising in solar flares.

[1)]Lebedev Physical Institute, Russian Academy of Sciences, Leninskii pr. 53, Moscow, 119991 Russia.
[2)]National Research Nuclear University MEPhI, Kashirskoe sh. 31, Moscow, 115409 Russia.
[3)]Scientific Research Institute for System Analysis, Russian Academy of Sciences, Moscow, 117218 Russia.
[*]E-mail: soutch@mail.ru

The goals of the GAMMA-400 experiment are continuous long-term (up to 100 days) observations of high-energy γ-ray emission from the Galactic center; Fermi bubbles; the Crab nebula; and the constellations Vela, Geminga, and Cygnus, as well as the Sun, etc., with unprecedented angular ($\sim$0.01° for $E_\gamma > 100$ GeV) and energy ($\sim$1% for $E_\gamma > 100$ GeV) resolutions, which are significantly better than those of the Fermi-LAT [3] and AGILE [4] γ-ray telescopes currently operated in orbit, as well as those of the operated and projected ground-based γ-ray telescopes VERITAS [5], MAGIC [6], H.E.S.S. [7], and CTA [8].

GAMMA-400 GAMMA-RAY TELESCOPE

GAMMA-400 is a satellite γ-ray telescope that uses, for recording γ-ray emission, the conversion of gamma rays propagating in a converter into electron–positron pairs. The conversion electron and positron move in the direction of photon motion and are recorded by detector systems. The basic mode of GAMMA-400 is precision measurements of individual regions of the celestial sphere, e.g., the region of the Galactic center, with the duration of the continuous observation of up to 100 days in a highly elliptical orbit, where the passages through the radiation belts and the shadowing of the field of view of the γ-ray telescope by the Earth are virtually absent, for the following initial parameters: an apogee of 300 000 km, a perigee of 500 km, and an inclination of 51.4°.

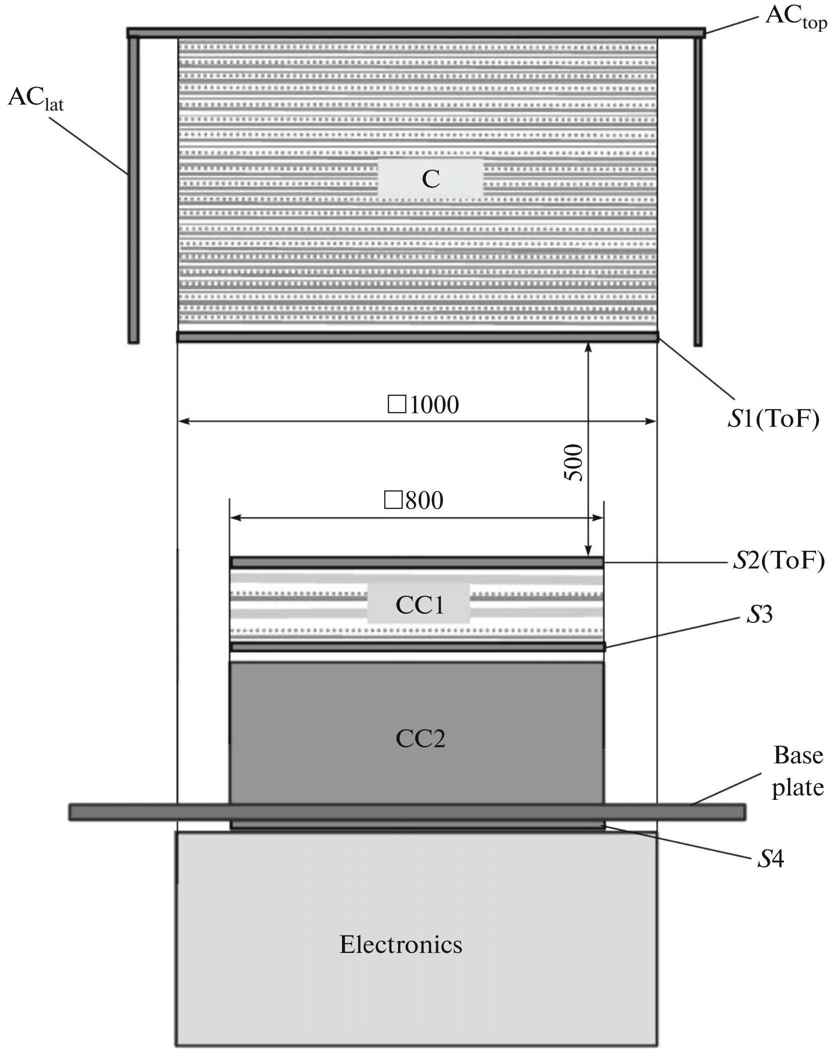

Fig. 1. Layout of the GAMMA-400 γ-ray telescope: anticoincidence system (AC) (top and lateral detectors), converter-tracker (C), time-of-flight system (ToF), parts of coordinate-sensitive calorimeter (CC1 and CC2), and scintillation detectors of the calorimeter ($S3$ and $S4$).

The basic detector systems of the GAMMA-400 γ-ray telescope are an anticoincidence system, a converter-tracker, a time-of-flight system, a calorimeter, and scintillation detectors of the calorimeter (Fig. 1). For manufacturing detectors, technologies well-tested in space experiments and high-energy physics were selected.

The anticoincidence system (AC) provides the separation of cosmic gamma rays against the background of a significantly higher flux of protons and electrons of primary cosmic rays with an efficiency of separation of gamma rays against the background of charged particles better than 0.999995. The detector system of AC surrounds the converter from five sides (top detector AC$_{top}$ and four lateral detectors AC$_{lat}$).

The top detector AC$_{top}$ is a two-layer detector from plastic scintillator BC-408. The upper layer consists of ten strips; the bottom layer consists of 11 strips parallel to the upper layer; the slits between the strips of one layer are shifted relative to the strips of the other, which ensures the overlap of the slits. Four lateral anticoincidence detectors AC$_{lat1}$–AC$_{lat4}$, which are similar in design to AC$_{top}$, are oriented perpendicularly to the plane of the top detector AC$_{top}$ on the four sides of the tracker-converter. The use of the two-layer construction with overlapping slits allows us to achieve the value of 0.999995 for the separation of γ-ray events against the charged-particle background.

The converter-tracker (C) is intended for (i) converting gamma rays into electron—positron pairs and recording them and (ii) determining the gamma-ray arrival direction with a high accuracy, which allows us to obtain a high angular resolution of the GAMMA-400 γ-ray telescope.

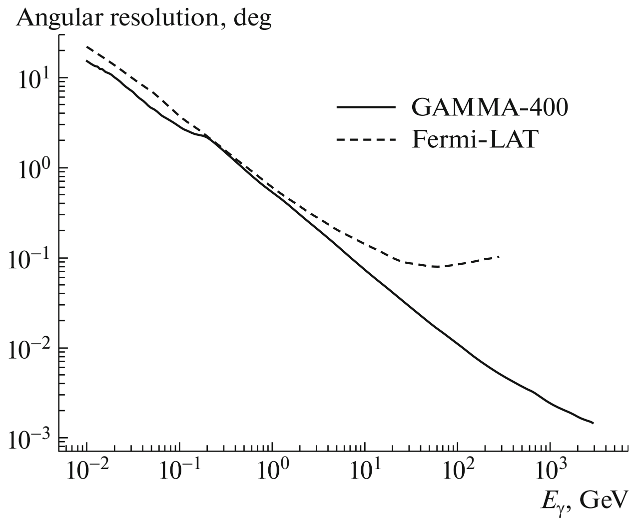

Fig. 2. Energy dependence of the angular resolution of the GAMMA-400 γ-ray telescope. The analogous dependence for Fermi-LAT is shown for the sake of comparison.

The converter-tracker C consists of 22 pairs of planes of silicon strip detectors (X and Y coordinates) located on 23 honeycombs with a strip pitch of 80 μm and a analog readout, which greatly improves a spatial accuracy. On the top 20 panels, there are tungsten converters of thickness 0.025 r.l. (radiation length unit). The total thickness of the converter-tracker for vertical incidence of particles is about 1 r.l.

The chosen design of the converter-tracker (and of the γ-ray telescope as a whole) provides a significant improvement in the angular resolution in comparison with Fermi-LAT in over almost the whole energy range from about 20 MeV to about 1000 GeV, especially from 10 GeV, and is about 0.01° at the energy of 100 GeV (Fig. 2). This is achieved by (i) improving the spatial resolution of silicon strip detectors (use of strip detectors with a pitch of 80 μm versus 225 μm in Fermi-LAT and of an analog readout instead of a binary one in Fermi-LAT); (ii) employing a long flight base from the strip detectors of the converter to the strip detectors of the calorimeter; (iii) significantly reducing the background level from the backscattered flux owing to the large distance from the converter to the calorimeter, about 100 cm versus about 10 cm in Fermi-LAT; and (iii) additionally using a fast trigger, which provides the reduction of the background from cosmic radiation, about 50 ns versus about 1.5 μs in Fermi-LAT.

The time-of-flight system (ToF) is intended for separating events caused by converted gamma rays moving in the telescope's aperture from the upper detector ($S1$) to the lower one ($S2$) against background events caused by gamma rays and particles moving in the opposite direction.

ToF consists of the upper $S1$ and lower $S2$ scintillation detectors. Each detector consists of two layers of plastic scintillator BC-408.

The coordinate-sensitive calorimeter is intended for measuring the energy of γ-ray emission. It consists of two parts: a position-sensitive calorimeter (CC1) and an electromagnetic calorimeter (CC2).

CC1 is intended for determining the spatial position of the axis of the electromagnetic shower from the recorded gamma rays and for measuring the electromagnetic-shower energy released in it from the recorded gamma rays.

CC1 consists of two groups. Each group consists of two detectors: a scintillation detector of CsI(Tl) crystals overlapping the sensitive area and a two-layer (X, Y) silicon strip detector with a strip pitch of 80 μm and an analog readout. The thickness of CC1 is about 2 r.l. The use of CC1 allows us to determine the position of the axis of the electromagnetic shower with a high accuracy.

CC2 is intended for measuring the released energy of the electromagnetic shower from recorded gamma rays with a high energy resolution, determining the shower profile, and rejecting protons.

CC2 consists of CsI(Tl) scintillation crystals. The thickness of CC2 for the normal incidence of particles is 20 r.l.

The calorimeter (CC1 and CC2) of total thickness about 22 r.l. for the normal incidence of particles (about 8.5 r.l. in Fermi-LAT) will allow us to obtain an energy resolution significantly better than that of Fermi-LAT beginning from the energy of 10 GeV; it will be about 1% at the energy of 100 GeV (Fig. 3).

The scintillation detectors of the calorimeter (SDC), which consist of plastic scintillation detectors $S3$ and $S4$, are intended for determining the energy release from the recorded particles and generating signals for the formation of a trigger; separating single-particle events for a calibration; and determining, with detector $S4$, the leakage of electromagnetic-shower particles escaping from the calorimeter.

The design of the SDC detectors is similar to the design of the ToF detectors.

When recording gamma rays of energy more than a few tens of GeV units, there arises a flux of backscattered (BS) particles, (mainly gamma rays of energy about 1 MeV) formed during the development of the electromagnetic shower in the calorimeter, which move in the direction opposite to the anticoincidence detector. This flux causes false actuations of the AC system, creating an imitation of the passage of charged particles, as well as imaginary signals in the strip detectors of the converter-tracker. The flux of BS particles can significantly reduce the

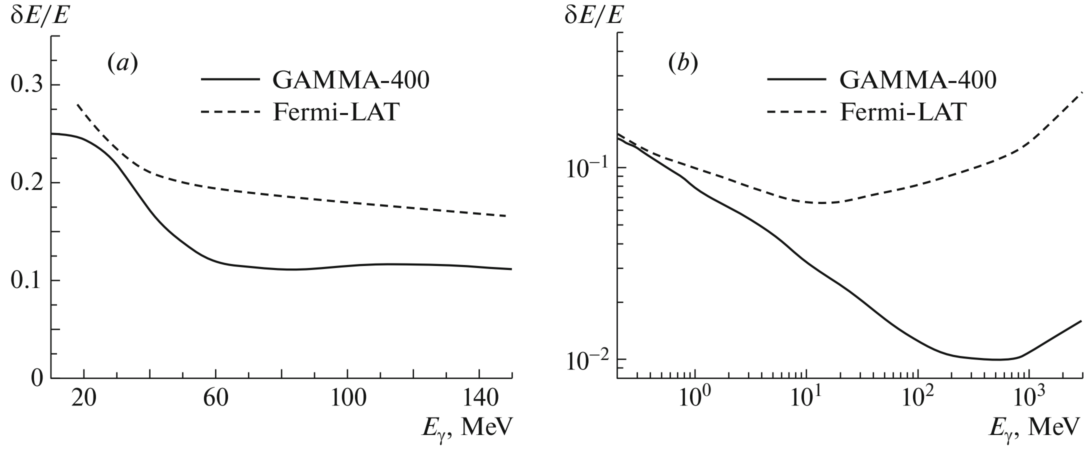

Fig. 3. The energy resolution of the GAMMA-400 γ-ray telescope as a function of the gamma-ray energy in the ranges of (*a*) 20–140 MeV and (*b*) 0.2–1000 GeV. The analogous dependences for Fermi-LAT are shown for the sake of comparison.

efficiency of the γ-ray telescope in recording gamma rays of energy higher than several tens of GeV units.

The following design features used in GAMMA-400 significantly reduce the effect of BS particles on recording high-energy γ-ray emission: (i) the segmentation (including the two-layer structure) of AC detectors, which reduces the probability of triggering AC segments from BS particles; (ii) the use of CC1, which significantly reduces the flux of BS particles formed in CC2; and (iii) an increased distance from CC2 to the converter-tracker (it is equal to 100 cm).

Calculations showed that, for the chosen design of the γ-ray telescope, the number of events that are associated with the flux of BS particles and which could be interpreted as charged particles and should be excluded from detection is not more than a few percent even for gamma rays of energy 1000 GeV.

Moreover, a time method based on measuring the time of particle flight between the detectors of these systems is used to reduce the flux of BS particles. Its signal in AC appears later than the event occurring in ToF $S1$ and triggering the beginning of detection, and this makes it possible to separate events induced by BS particles [9].

The triggers for recording gamma rays in GAMMA-400 are the actuation of ToF $S1$ earlier than $S2$ and the absence of the AC signal.

The delay between triggering and readout of information from the detectors is about 50 ns.

The use of a faster trigger allows us to reduce significantly the influence of the cosmic-radiation background in GAMMA-400.

CONCLUSIONS

The unprecedented characteristics of GAMMA-400 (an angular resolution of about 0.01° for $E_\gamma >$ 100 GeV and an energy resolution of about 1% for $E_\gamma > 100$ GeV), along with a continuous long-term (up to 100 days) observation of individual regions of the celestial sphere, the Galactic center, etc., will allow us to make significant advances in precision studies of discrete sources of γ-ray emission; measurements of the energy spectra of Galactic and extragalactic diffuse γ-ray emission; and measurements of fluxes of gamma rays and the electron–positron cosmic-ray component, which can be associated with the annihilation or decay of dark-matter particles. The launch of the space observatory with the GAMMA-400 γ-ray telescope is scheduled for 2025–2026.

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