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Design and Performance of the GAMMA-400 Gamma-Ray Telescope for Dark Matter Searches

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Abstract. The GAMMA-400 gamma-ray telescope is designed to measure the fluxes of gamma-rays and cosmic-ray electrons + positrons, which can be produced by annihilation or decay of the dark matter particles, as well as to survey the celestial sphere in order to study point and extended sources of gamma-rays, measure energy spectra of Galactic and extragalactic diffuse gamma-ray emission, gamma-ray bursts, and gamma-ray emission from the Sun. GAMMA-400 covers the energy range from 100 MeV to 3000 GeV. Its angular resolution is $\sim 0.01^\circ$ ($E_\gamma > 100$ GeV), the energy resolution $\sim 1\%$ ($E_\gamma > 10$ GeV), and the proton rejection factor $\sim 10^6$. GAMMA-

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400 will be installed on the Russian space platform Navigator. The beginning of observations is planned for 2018.

Keywords: gamma-ray telescope, dark matter, cosmic gamma-ray emission

PACS: 95.35+d, 95.55.-n, 95.55.Ka, 95.85.Pw, 98.70.Rz

INTRODUCTION

In the list of very important issues in modern cosmology at the beginning of XXI Century, Nobel Laureate Academician V. L. Ginzburg noted “the issue of dark matter and its detection” [1]. Today it is believed that the dark matter density ($\sim 25\%$) in the universe is several times greater than the barionic matter density ($\sim 5\%$). One of the candidates for dark matter particles are WIMPs, Weakly Interacting Massive Particles. Scientists from around the world are trying to find WIMPs, using both direct and indirect methods of detection. Indirect methods are based on the detection in the cosmic-ray radiation of the annihilation or decay products of WIMPs, which can be regular particles and their anti-particles (neutrinos, electrons, positrons), as well as gamma-rays. Gamma-rays play an important role, as they propagate from the source without a significant absorption and, therefore, can be used to determine the direction to the source of the emission.

An analysis of observations of the region near the Galactic center by the Fermi Large Area gamma-ray Telescope (Fermi-LAT) hints at a feature in the spectrum of gamma-ray emission near ~ 130 GeV [2]. Such a feature, if confirmed, would be a unique signature of new physics, but its reliable detection requires significant improvements in the angular and energy resolutions of future instruments [3-7].

These challenges are addressed by a proposed new gamma-ray telescope GAMMA-400. GAMMA-400 will have a unique capability to resolve gamma-ray lines predicted to be signatures of the decay of WIMPs, and to determine the location of their source(s).

THE GAMMA-400 GAMMA-RAY TELESCOPE

The GAMMA-400 gamma-ray telescope is designed to measure the gamma-ray and cosmic-ray electron + positron fluxes, which may be associated with annihilation or decay of dark matter particles, as well as to survey the sky in order to search for and study gamma-ray sources, to measure the energy spectra of Galactic and extragalactic diffuse gamma-ray emission, to study gamma-ray bursts and gamma-ray emission from the Sun in the energy range from 100 MeV to 3000 GeV.

Previously described in [8,9], the GAMMA-400 physical scheme was recently modified and is presented along with its basic parameters in Figure 1. The GAMMA-400 gamma-ray telescope includes:

- top (AC_{top}) and lateral (AC_{lat}) anticoincidence detectors;
- converter-tracker C, which represents 10 interleaved by tungsten (x,y) planes with mutually perpendicular strips of silicon-strip coordinate detectors with 0.1 mm strip pitch. The total thickness of the converter-tracker is 1.0 radiation length (X_0). Currently Italian and US scientists consider the possibility of

- adding to converter-tracker 15 additional silicon (x,y) planes to improve the instrument capabilities at low energies below ~ 300 MeV;
- time-of-flight system (TOF) between the S1 and S2 scintillation detectors separated by a distance of 500 mm;
 - position-sensitive calorimeter, consisting of 2 parts:
 - a) 4-layer imaging CC1. Each layer contains CsI(Tl) crystals and silicon-strip (x,y) planes with mutually perpendicular 0.5 mm pitch strips. CC1 thickness is $3 X_0$.
 - b) Electromagnetic CC2 made of $25 \times 25 \times 250$ mm³ BGO crystals. The thickness of CC2 is $22 X_0$. The total calorimeter (CC1 + CC2) thickness is $25 X_0$ for the normal incidence particles, and $\sim 70 X_0$ for the lateral incidence;
 - S3 and S4 scintillation detectors;
 - Lateral calorimeter detectors LD;
 - Neutron detector ND.

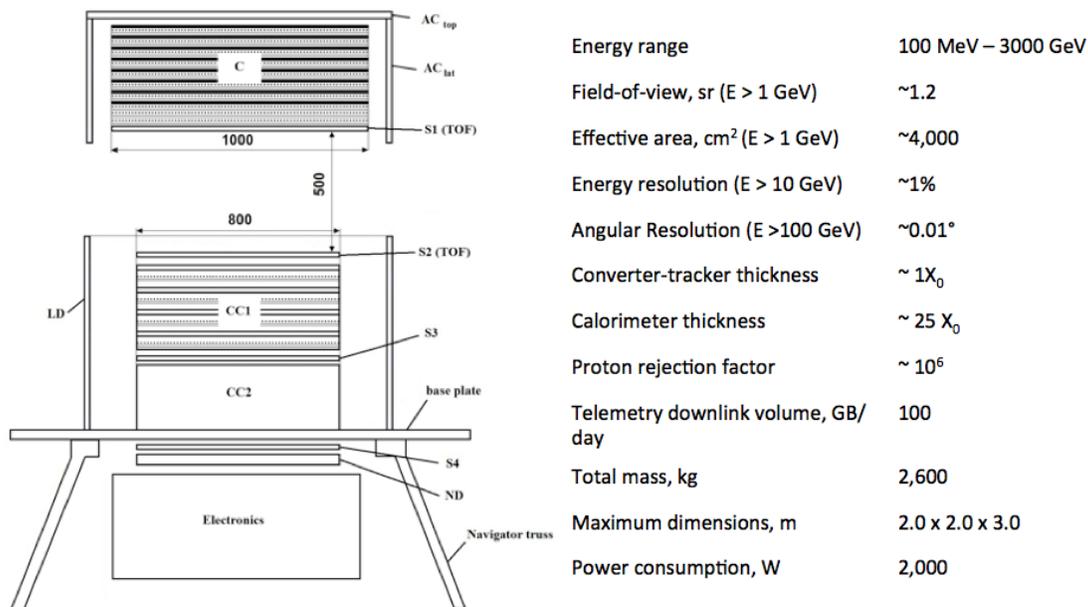


FIGURE 1. GAMMA-400 physical scheme and its basic parameters. AC_{top} is top an anticoincidence scintillation detector; AC_{lat} are lateral anticoincidence detectors; C is a converter-tracker; S1 (TOF) and S2 (TOF) are scintillation detectors of the time-of-flight system; CC1 is imaging calorimeter; CC2 is electromagnetic calorimeter; S3 and S4 are scintillation detectors; ND is neutron detector; LD are lateral detectors.

A gamma-ray photon is converted into an electron-positron pair in the converter-tracker, which then is detected in the instrument detectors. Anticoincidence detectors are used to identify the gamma-rays, and the time-of-flight system determines the direction of the incident particles and forms the telescope aperture. The electromagnetic shower created by the electron-positron pair develops in both parts of the calorimeter and is detected in the calorimeter and scintillation detectors S3 and S4.

Gamma-rays are detected by the absence of a signal in AC, while electrons (positrons) are detected by the presence of a signal in AC, when moving downward and from lateral directions.

Using the calorimeter with thickness $\sim 25 X_0$ extends the particle measurable energy range up to several TeV and increases the gamma-ray telescope energy resolution up to $\sim 1\%$ at energies more than 10 GeV. The energy dependence of the GAMMA-400 energy resolution for incident gamma-rays was simulated using Monte Carlo techniques and is shown in Figure 2a along with the same dependence for the Fermi-LAT [10] for comparison. It is seen that in the energy range from 10 GeV to ~ 10 TeV the energy resolution is $\sim 1\%$, which is extremely important for resolving the gamma-ray lines from the decay of the dark matter particles.

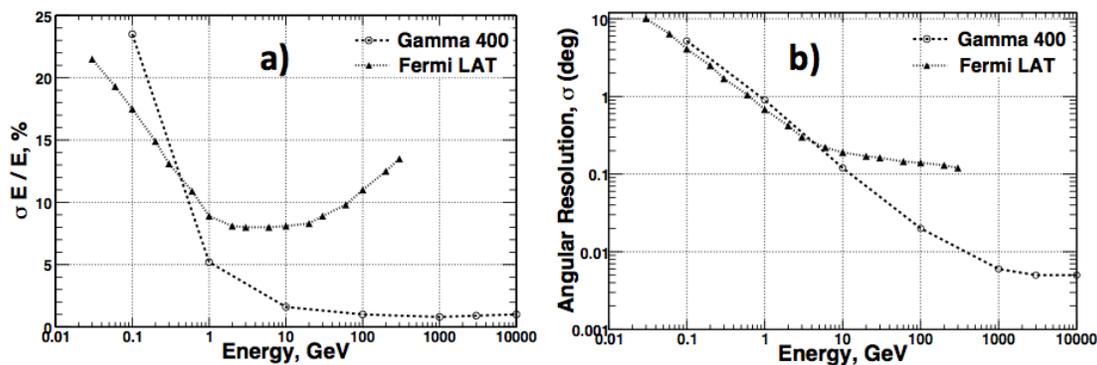


FIGURE 2. Energy resolution (a) and angular resolution (b) for the GAMMA-400 and Fermi LAT gamma-ray telescopes

High angular resolution is achieved by determining the conversion point in a multilayer converter-tracker and the reconstruction of the shower axis in CC1. This method allows the high angular resolution of $\sim 0.01^\circ$ to be achieved at energies more than 100 GeV (Figure 2b) and enables an accurate localization of the source of the gamma-ray lines.

High-energy incident particles create a backplash (upward moving products of the shower) in the calorimeter. To prevent the detection of the backplash particles in the AC (thereby creating a self-veto), we use the method of separation of incident and backplash particles in the AC by the time-of-flight along with the segmentation of the AC as used in Fermi-LAT [10,11] and AGILE [12].

The proton rejection factor of $\sim 10^6$, critical parameter for the background rejection, will be achieved by using the calorimeter and the neutron detector together with other instrument subsystems.

Table 1 shows the basic parameters of the existing and planned space-based (Fermi [10], AMS-2[13]) and ground-based (MAGIC [14], H.E.S.S.-II [15], and CTA [16]) experiments. It can be seen that the GAMMA-400 is well-suited for the search for the dark matter signatures including narrow gamma-ray lines.

The GAMMA-400 space observatory will be installed on the Navigator service platform designed by Lavochkin Association. It will be launched into high-elliptic orbit with initial parameters: an apogee of 300,000 km, a perigee of 500 km, and an inclination of 51.8° . After approximately half a year the orbit will evolve into an

almost circular orbit with radius of $\sim 150,000$ km, i.e. the observatory will fully leave the Earth's radiation belt. The expected lifetime of the observatory will be more than 7 years. The launch of the space observatory is planned for 2018.

TABLE 1. A comparison of basic parameters of existing and planned space- and ground-based experiments

	Space-based experiments			Ground-based experiments		
	Fermi LAT	AMS-2	GAMMA-400	H.E.S.S.-II	MAGIC	CTA
Energy range, GeV	0.02-300	10-1000	0.1-3000	>30	>50	>20
Field-of-view, sr	2.4	0.4	~ 1.2	0.01	0.01	0.1
Effective area, m ²	0.8	0.2	~ 0.4	10 ⁵	10 ⁵	10 ⁶
Angular resolution (E>100 GeV)	0.2°	1.0°	$\sim 0.01^\circ$	0.07°	0.05°	0.06°
Energy resolution (E>100 GeV)	10%	2%	$\sim 1\%$	15%	15%	10%

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