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Modifications of a method for low energy gamma-ray incident angle reconstruction in the GAMMA-400 gamma-ray telescope

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Abstract. The GAMMA-400 gamma-ray telescope is designed to measure the gamma-ray fluxes in the energy range from ~20 MeV to ~1 TeV, performing a sensitive search for high-energy gamma-ray emission when annihilating or decaying dark matter particles. Such measurements will be also associated with the following scientific goals: searching for new and studying known Galactic and extragalactic discrete high-energy gamma-ray sources (supernova remnants, pulsars, accreting objects, microquasars, active galactic nuclei, blazars, quasars). It will be possible to study their structure with high angular resolution and measuring their energy spectra and luminosity with high-energy resolution; identify discrete gamma-ray sources with



known sources in other energy ranges. The major advantage of the GAMMA-400 instrument is excellent angular and energy resolutions for gamma rays above 10 GeV. The gamma-ray telescope angular and energy resolutions for the main aperture at 100-GeV gamma rays are $\sim 0.01\%$ and $\sim 1\%$, respectively.

The motivation of presented results is to improve physical characteristics of the GAMMA-400 gamma-ray telescope in the energy range of ~ 20 -100 MeV, most unexplored range today. Such observations are crucial today for a number of high-priority problems faced by modern astrophysics and fundamental physics, including the origin of chemical elements and cosmic rays, the nature of dark matter, and the applicability range of the fundamental laws of physics. To improve the reconstruction accuracy of incident angle for low-energy gamma rays the special analysis of topology of pair-conversion events in thin layers of converter performed. Choosing the pair-conversion events with more precise vertical localization allows us to obtain significantly better angular resolution in comparison with previous and current space and ground-based experiments. For 50-MeV gamma rays the GAMMA-400 gamma-ray telescope angular resolution is better than 5° .

1. Introduction

The main goal for the GAMMA-400 gamma-ray telescope mission is to perform a sensitive search for signatures of dark matter particles in high-energy gamma-ray emission. Measurements will also be associated with the following scientific goals: detailed study of the galactic center region, investigation of point and extended gamma-ray sources, studies of the energy spectra of the Galactic and extragalactic diffuse emissions. To perform these measurements the GAMMA-400 gamma-ray telescope possesses unique physical characteristics for energy range from ~ 20 MeV to ~ 1 TeV in comparison with previous and current space and ground-based experiments. The major advantage of the GAMMA-400 instrument is excellent angular and energy resolution for gamma rays above 10 GeV. The gamma-ray telescope angular and energy resolutions for the main aperture at 100-GeV gamma rays are $\sim 0.01^\circ$ and $\sim 1\%$, respectively.

The special goal is to improve physical characteristics in the low-energy range from 20 MeV to 100 MeV. Minimizing the amount of dead matter in the telescope aperture allows us to obtain the angular resolution better than in the current space missions in this energy range. The gamma-ray telescope angular resolution at 50-MeV gamma rays is better than 5° . We report the method providing these results.

2. The GAMMA-400 gamma-ray telescope

The GAMMA-400 physical scheme shown in figure 1. From the top, the telescope consists of the following layers:

- an anticoincidence system (AC) is composed by plastic scintillators, located both on top and on the lateral side of the apparatus. The system is essentially used to veto charged particles.
- a converter-tracker system (C) consists of 22 layers. 20 layers of converter-tracker have high-Z material (tungsten) in which γ -rays incident on the instrument can convert to an $e+e^-$ pair. The converter planes are interleaved with position-sensitive detectors that record the passage of charged particles, thus measuring the tracks of the particles resulting from pair conversion. The position-sensitive detectors are double (x, y) silicon strips (pitch 0.08 mm). The lowest two (x, y)-planes have no tungsten converter material. The total converter-tracker thickness is about $\sim 1 X_0$ (X_0 is the radiation length). The converter-tracker information used for precisely determination of the conversion point and the direction of each incident particle. This information provides also the possibility to measure polarization of gamma-rays.
- a Time of Flight system (TOF) is formed by plastic scintillators S1 and S2, separated by approximately 500 mm. This system is used both to generate the trigger for the apparatus and to reject albedo particles by measuring their velocity.
- a deep electromagnetic calorimeter CC. The total calorimeter thickness is $\sim 21 X_0$ or $\sim 1.0 \lambda_0$ (where λ_0 is nuclear interaction length). Using a deep calorimeter allows us to extend the

energy range up to several TeV for gamma rays, and to reach an energy resolution of approximately 1% above 100 GeV.

- the scintillation detector S3 improves hadrons and electromagnetic showers separation.

3. Method to reconstruct incident angle for low energy gamma

The method to reconstruct the initial angle of incident low-energy gamma in the GAMMA-400 instrument is describe in [1]. In this method, the effect of multiple scattering of pair conversion components used to involve energy correction in angle reconstruction procedure.

The brief description of the method is following. When the energy of the incident gamma is less than 1 GeV, an electron-positron pair produced due to conversion of initial gamma can be readily tracked individually. The information from double (x, y) silicon strip coordinate detectors in converter-tracker provides the possibility to split the total space development of conversion event in two perpendicular plane projections. Each projection considered independently (figure 2).

Due to multiple scattering, electrons and positrons are deflected from initial direction and their trajectories can be fitted by a circular arc. Only three consecutive layers just below the conversion point are considered, from which ‘left’ and ‘right’ track can be identified. Then for each track the position of conversion point in the tungsten layer is estimated: $x_{L(0)}$ and $x_{R(0)}$. From numerical Monte-Carlro simulations, the dependence of the arc curvature from the kinetic energy were obtained for the converter-tracker layers. Then for each ‘left’ and ‘right’ track the corresponding kinetic energy E_L and E_R is estimated.

The position of conversion point in tungsten layer is farther corrected by

$$X_{CONV} = \frac{x_{L(0)} \times E_L + x_{R(0)} \times E_R}{E_L + E_R}.$$

Then the location X_{CONV} using for the calculation of the plane component of the initial gamma incident angle [1]:

$$\alpha_x = \frac{\alpha_x^L \times E_L + \alpha_x^R \times E_R}{E_L + E_R}.$$

The same algorithm is applied for the calculation of another plane angle α_y . From the known values of plane angles, it is straight forwards to obtain spherical zenith and polar angles.

When simulating the support structure for the detectors and converter foil planes taken into account to check its influence on converter-tracker performance. We applied a similar construction as it is in

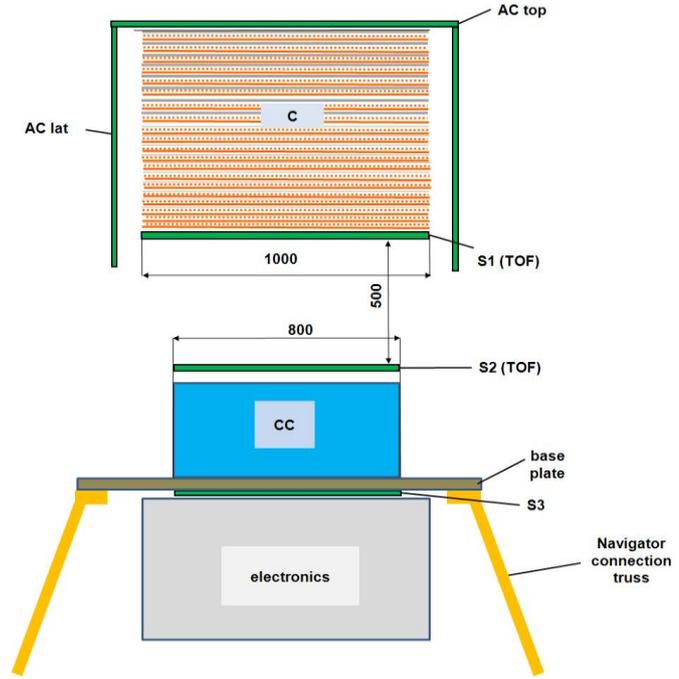


Figure 1. The GAMMA-400 physical scheme.

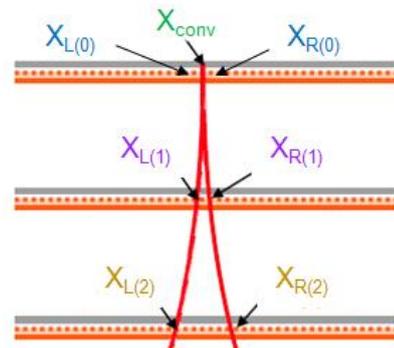


Figure 2. Schematic illustration of the conversion pair topology. X_{conv} is the coordinate estimation of the point in a tungsten layer where a conversion occurred. Red levels: double planes of silicon strips; grey levels: tungsten layers ($0.025 X_0$)

Fermi-LAT mission [2, 3]. The converter-tracker tower consists of the 23 trays supported by carbon-composite sidewalls with thickness of 0.8 mm. Each tray includes aluminum honeycomb core and has thickness about 3 cm. The total thickness of the material just from above each tungsten foil is about $0.01 X_0$ and is comparable with thickness of tungsten layer $0.025 X_0$ for pair production (figure 3). The geometrical thickness of the matter above tungsten is 3 cm that two orders of magnitude more, than geometrical thickness of converter foil (0.09 mm). For such structure, the accuracy of vertical localization of gamma conversion point is quite different for the cases depicted in figure 3. In the left part of figure 3, the conversion is occurred inside tungsten layer, and in the right part of figure 3, the conversion is appeared inside support matter. These two types of conversion events can be easily identified from the information of strip detectors in the tracker layer just under conversion point. In the “left” case, both pair components release energy in one strip (1 point event), while in the “right” case, each component of the pair releases energy in “own” strip (2 points event).

If one extract the events with 1-point topology, the accuracy of angular reconstruction appears significantly better than for events with 2-points topology. The results of angle reconstruction are shown in figure 4 for incident gamma with energy 20 MeV. The initial gamma-ray direction were fixed as 2° for zenith angle and 45° for polar angle just to check the robustness of the algorithm out from vertical direction. Left panel of figure 4 contains the distributions over plane angle of gamma for one and two point topology. In right panel of figure 4, the same distributions, but for deviation angle between reconstructed direction and initial direction are shown. Angular resolution, defined as condition of 68% containment, for 1-point topology events is $\sim 10^\circ$ and for 2-point topology events is $\sim 15^\circ$.

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The energy dependence of angular resolution of the GAMMA-400 gamma-ray telescope presented in figure 5 for 1-point topology, 2-point topology, and combined (1 point and 2 points) topology events. The angular resolution of Fermi-LAT instrument for on-axis gamma is also shown [2]. The angular resolution for 1-point events in the GAMMA-400 converter-tracker is better than angular resolution obtained from Fermi-LAT simulation data for gamma-ray energy less, than 200 MeV. For gamma-ray energy range from 200 MeV to 1 TeV another method is used to reconstruct initial gamma-ray direction in the GAMMA-400 gamma-ray telescope [4]. The angular resolution of GAMMA-400 is significantly better than ones of Fermi-LAT, from gamma-ray energy of 10 GeV.

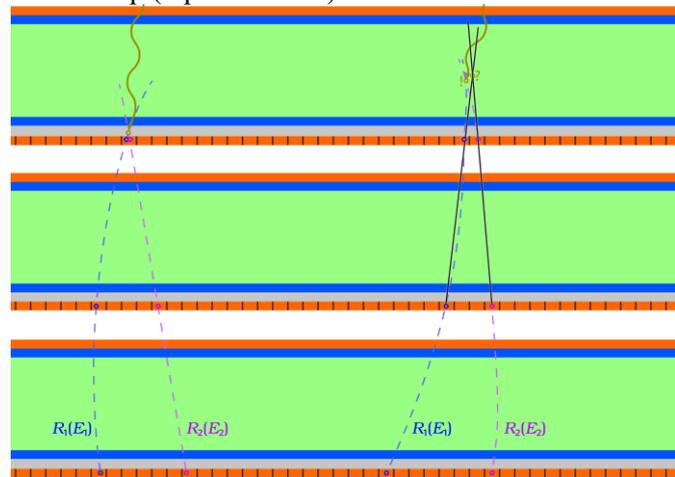


Figure 3. Two types of gamma conversion events in converter-tracker. Red levels: plane of silicon strips; blue levels: carbon-composite layers; green levels: aluminum honeycomb layers; grey levels: tungsten layers ($0.025 X_0$).

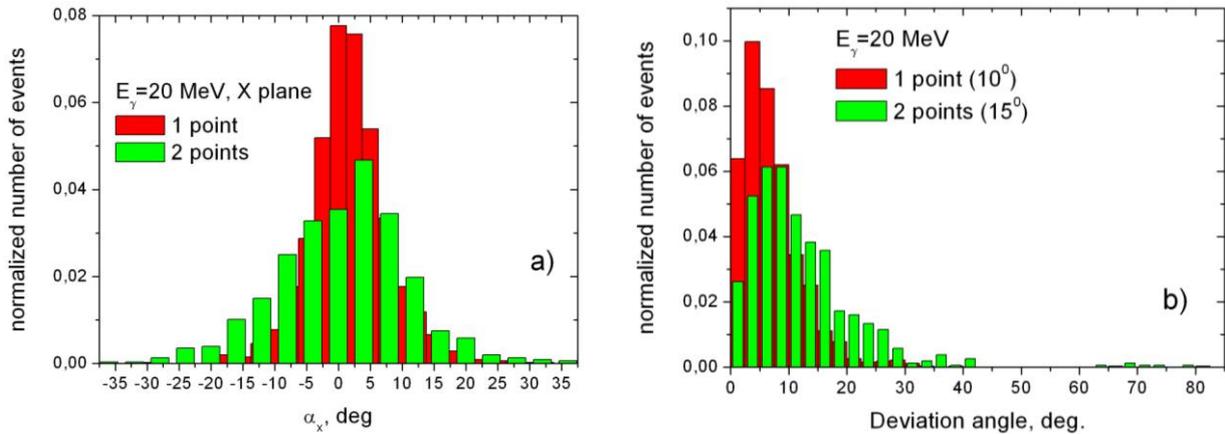


Figure 4. The results of angle reconstruction for incident gamma with the energy of 20 MeV. The distributions over plane angle of gamma for one and two point topology (a). The distributions of deviation angle between reconstructed direction and initial direction (b). Angular resolution is defined as condition of 68% containment.

4. Conclusion

To improve the reconstruction accuracy of incident angle for low-energy gamma rays the special analysis of topology of pair-conversion events in thin layers of converter was performed. Choosing the pair-conversion events with more precise vertical localization allows us to improve angular resolution. For 50-MeV gamma rays, the GAMMA-400 gamma-ray telescope angular resolution is 4.6° that is several degrees better than in the Fermi-LAT mission.

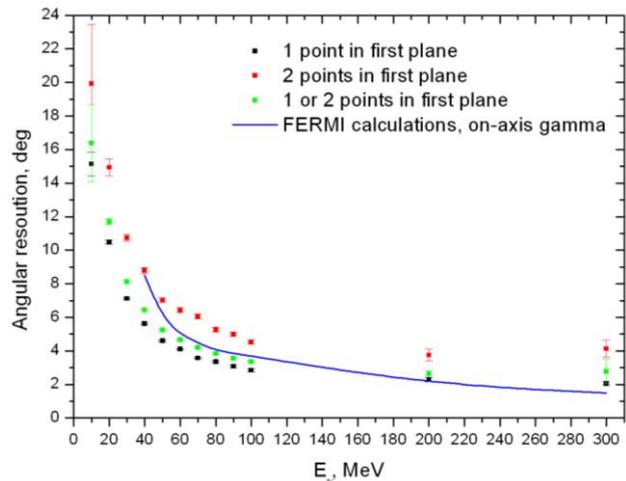


Figure 5. The energy dependence of angular resolution of the GAMMA-400 gamma-ray telescope. Black points: 1-point topology events; red points: 2 point-topology events; green points: 1 or 2 point topology events. The results of calculation for angular resolution in the Fermi-LAT instruments shown by blue line.

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