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ScienceDirect

Physics Procedia 74 (2015) 368 – 371

Physics Procedia

Conference of Fundamental Research and Particle Physics, 18-20 February 2015, Moscow, Russian Federation

Method of Incident Low-Energy Gamma-Ray Direction Reconstruction in GAMMA-400 Gamma-Ray Space Telescope

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Abstract

Gamma-telescope GAMMA-400 is designed to measure fluxes of γ-rays and the electron–positron cosmic ray component possibly associated with dark matter particles annihilation or decay; and to search for and study in detail discrete γ-ray sources, to investigate the energy spectra of Galactic and extragalactic diffuse γ-rays, and to study γ-ray bursts (GRB) and γ-rays from the active Sun. GAMMA-400 gamma-ray space-based telescope scientific goals require fine angular resolution. GAMMA-400 is the pair production telescope. In the converter-tracker the incident gamma-quantum convert into electron-positron pair in the tungsten layer and then the tracks are registered by silicon-strip position-sensitive detectors. Multiple scattering processes become a significant obstacle in the incident gamma direction reconstruction for energies below several GeV. The method of utilising this process to improve the resolution is proposed in the presented work.

Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

Keywords: GAMMA-400; gamma-ray astronomy; angular resolution

1. Introduction

Under the RF Space Program for 2009–2015 and the RF Space Program developed for 2016–2025, work is now under way to create a space observatory with the GAMMA-400 scientific complex. The GAMMA-400 scientific

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Peer-review under responsibility of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
doi:10.1016/j.phpro.2015.09.196

complex is designed to study γ-ray emissions in the high-energy range and acquire data that will allow us to determine the nature of dark matter in the Universe and develop a theory of the origin of high-energy cosmic rays. The GAMMA-400 instrument is designed to resolve energy spectra peculiarities, which are expected in gamma-ray emission from areas where hypothetical dark-matter particles decay or annihilate into gamma rays or a gamma-ray photon and another particle. Temporal study of high-energy gamma-ray emission from discrete sources may shed light upon the nature of particle acceleration in these sources.

One of the important goals of the GAMMA-400 project is high-energy gamma-ray detection from the Galactic centre, where dark matter particles are likely to be concentrated. The telescope is required to have, inter alia, fine angular resolution to discern gamma rays efficiently from dark matter particles against the background diffuse emission. GAMMA-400 is expected to have angular and energy resolutions in the energy range of > 10 GeV much better than do Fermi/LAT [1–3] and AGILE [4] gamma-ray telescopes.

1. Gamma-telescope GAMMA-400

The physical scheme of the GAMMA-400 γ-ray telescope is shown in Fig. 1. The main aperture energy range for γ-rays and electrons (positrons) registration is from ~0.1 GeV to ~3.0 TeV. Gamma-quanta, electrons, positrons, and light nuclei can be also detected from the lateral directions.

Time and segmentation methods are used to reduce the influence of backscattering particles created when incident γ-rays interact with the calorimeter's matter and move in the opposite direction.

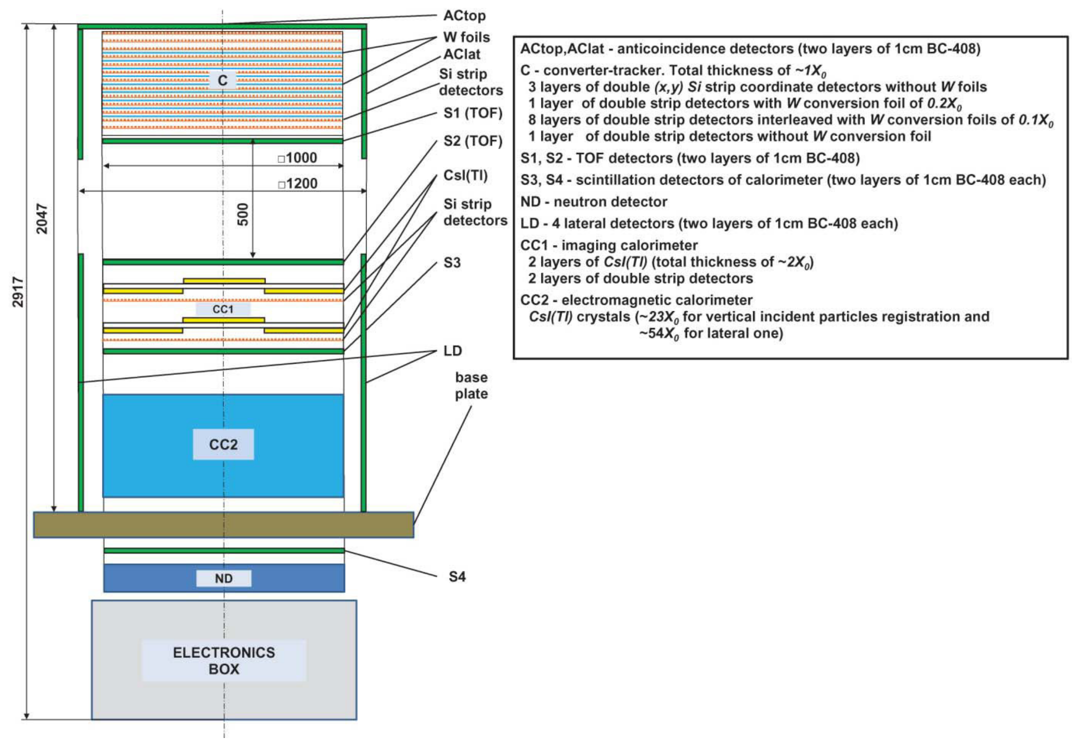

Fig. 1. Physical scheme of the GAMMA-400 gamma ray telescope: AC_{top}, is a top anticoincidence detector; AC_{lat}, are lateral anticoincidence detectors; C is a converter-tracker; S1 and S2 are scintillation detectors of the time-of-flight (TOF) system; CC1 and CC2 compose coordinate sensitive calorimeter; S3 and S4 are scintillation detectors; ND is a neutron detector.

Converter-tracker consists of 13 layers of silicon-strip detectors. Each layer consists of two silicon-strip planes with different *orientations X* and *Y*. Nine strip detectors started with the fourth one being preceded by tungsten conversion foils. The first foil thickness is 0.2 X_0 (where X_0 is the radiation length) next nine ones - 0.1 X_0. Than first three and last one strip layers in the converter-tracker are without preceded tungsten conversion foils. Gamma rays in the main aperture converted into electron-positron pairs in tungsten foils in the converter-tracker. These pairs are detected by ten layers of silicon strip position-sensitive detectors in the converter-tracker, Electromagnetic showers caused by pair components are developed inside the calorimeter and are registered in CC1, CC2 and S3 and S4 scintillation detectors. Two additional layers of silicon-strip detectors inside CC1 allow determining electromagnetic shower's start point. Anticoincidence detectors located around the converter-tracker help to identify γ-rays, while the time-of-flight system determines the direction of the incident particles. Gamma-quanta in the main aperture are identified by absence of signal in the AC taking into account methods of backsplash rejection specially designed for GAMMA-400. Electrons (positrons) and nuclei are recognized by presence of signals in AC.

2. Reconstruction of the direction

During the Monte-Carlo simulation, a basic selection is done. There must be signals both in S1 and S2. Moreover, the first hit in S1 is required to be earlier than that in S2. Besides, four lowest silicon-strip planes (two orientations by two layers) in the converter must be triggered. No further processing is done with any rejected event.

When the energy of the incident gamma ray is $\lesssim$ 10 GeV, an electron-positron pair produced in the primary conversion — i.e. a pair production process suffered by the gamma-ray photon being detected — can be readily tracked individually.

The method is to find a somewhat 'weighted bisector' of pair tracks in each orientation with weights being estimated by a track curvature. We use here the fact that mean curvature due to multiple scattering decreases with rise of kinetic energy.

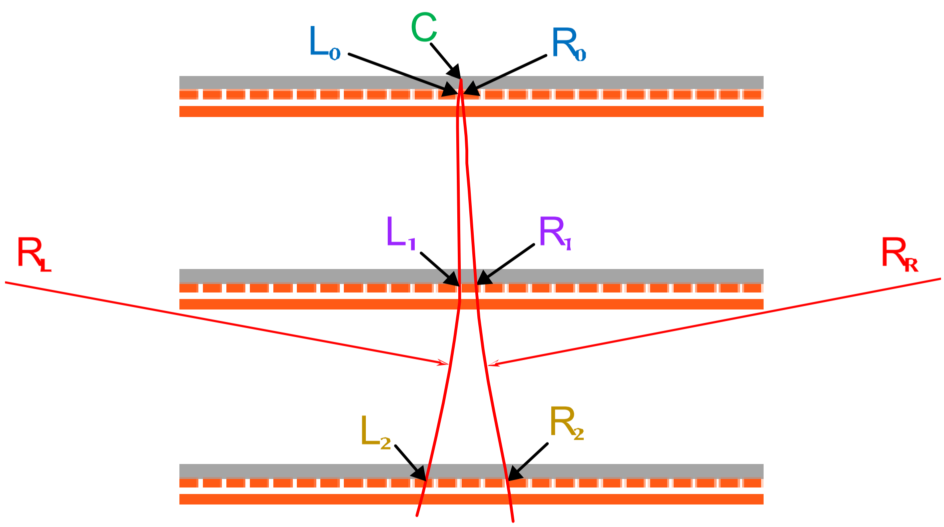

Fig. 2. Schematic illustration of using the method involved. Here shown are the points used in the reconstruction algorithm. C is a point in tungsten where a conversion occurred. L_i and R_i are strips where electron or positron hits a converter's silicon layer. Three consecutive layers directly below converting tungsten layer are considered.

Beforehand, the relation between statistical mode of radius of curvature and electron (positron) energy is calculated using Monte-Carlo simulation.

The following procedure is implemented.

First, the tungsten layer W in which a primary conversion occurs is determined. This layer is the one with no tracker signal above and with at least three consecutive directly below (in each of the two orientations). To be specific, we define the silicon layer (two strip planes) immediately below W to be number $i = 0$; others are assigned numbers 1 and 2 (see Fig. 2). In the following, we shall consider one orientation (X), another one (Y) is processed similarly.

Note that strictly speaking, the two tracks cannot be surely identified, as the two pair components may cross and alter their relative position to the opposite one from one layer to another. The method in question assumes that the left components in each layer constitute the L track and the right ones make the R track.

Then we obtain the coordinate X_C of the conversion point C. To do this, first approximations of the two directions are computed via weighted linear fit. We fit points L_1, L_2, L_3 with the last one's weight being 10 times smaller than that of the others, and the fitted line intersects W layer at point C_L; the same is done with R-points, producing C_R.

Radii of curvature R_L and R_R (see Fig. 1a) are defined to be the radii of circles passing the three points, (L_1, L_2, L_3) and (R_1, R_2, R_3) respectively. They do not describe the curvature in its usual sense but can serve as a rough estimation of electron (positron) energy using pre-calculated relation between R and E. Thus, we have now estimations E_L and E_R. Now, point C is defined by

$$X_C = \frac{E_L X_{C_L} + E_R X_{C_R}}{E_L + E_R}.$$

Now that we have got the fourth point on the tracks — both L and R — the linear fit described above is redone with new point triples: (C, L_1, L_2) and (C, R_1, R_2). Just as before, the last point's weights are reduced tenfold. Two straight tracks are obtained with angles α_L and α_R from the vertical. The angle

$$\alpha_X = \frac{E_L \alpha_L + E_R \alpha_R}{E_L + E_R}$$

together with similarly evaluated α_Y is considered as a direction of the incident gamma. More precisely, the direction is codirectional to the vector ($\tan(\alpha_X)$, $\tan(\alpha_Y)$, 1).

3. Conclusion

This method to reconstruct incident low-energy gamma-ray direction in GAMMA-400 gamma-ray space telescope provides high angular resolution for low energy gammas. GAMMA-400 angular resolution will be 2 degrees at 10^2 MeV. It is 50% better than could be for standard Kalman filter.

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