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NUCLEAR EXPERIMENTAL TECHNIQUE

A Technique for Selecting γ Rays with Energies above 50 GeV from the Background of Charged Particles in the GAMMA-400 Space-Based γ-Ray Telescope

M. D. Kheymits[a]*, A. M. Galper[a, b], I. V. Arkhangelskaja[a], A. I. Arkhangelskiy[a],
Yu. V. Gusakov[b], V. G. Zverev[a], V. V. Kadilin[a], V. A. Kaplin[a], A. A. Leonov[a],
P. Yu. Naumov[a], M. F. Runtso[a], S. I. Suchkov[b], N. P. Topchiev[b], and Yu. T. Yurkin[a]

[a] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute),*
Kashirskoe sh. 31, Moscow, 115409 Russia

[b] *Lebedev Physical Institute, Russian Academy of Sciences,*
Leninskii pr. 53, Moscow, 119991 Russia

**e-mail: mcsaksik@gmail.com*

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Abstract—The task of selecting neutral γ rays from the background of charged particle fluxes, which arises in investigation of high-energy (>50 GeV) cosmic rays, is complicated by the presence of the backsplash effect. The backsplash is composed of a great number of low-energy (~1 MeV) particles produced in an electromagnetic shower being developed in the calorimeter of the γ-ray telescope. A technique of charged particle rejection using an anticoincidence system has been developed. A method for discriminating events of charged particle detection from γ-ray detection events accompanied by the backsplash phenomenon is proposed. This method is based on the difference of the signals in time and makes it possible to maintain a high detection efficiency even for high-energy γ rays.

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INTRODUCTION

The current status of basic research in cosmology, astronomy, particle physics, and cosmic ray physics poses a number of problems that cannot be solved without recourse to results of investigations into extraterrestrial high-energy γ-ray astronomy. As an example, we can mention the problem of clearing the nature of dark matter.

Typical γ-ray telescopes for energies ranging from tens of MeV to hundreds of GeV (e.g., GAMMA-1 [1], AGILE [2], EGRET [3], and Fermi/LAT [4]) are based on conversion process and contain three main parts: a tracker for determining the direction of an incident particle, a calorimeter for measuring its energy, and an anticoincidence detector surrounding the tracker for discriminating between events of γ-ray detection and charged-particle hit events that are considerably larger in number. In the tracker, layers of a high-Z material (as a rule, tungsten) in which electron–positron pairs are produced are interleaved with position-sensitive detectors (silicon strip plates) determining the direction of particle incidence. The self-triggered tracker efficiently detects low-energy γ rays, but its use for charged-particle rejection is problematic through the long response time of the strip detectors. Considerably faster scintillation detectors can be used to detect high-energy γ rays. This allows one to discriminate between charged particles and the so-called backsplash—particles that have been produced in the calorimeter shower and returned to the anticoincidence detector. The backsplash may substantially reduce the γ-ray detection efficiency at energies exceeding tens of GeV.

In this paper, we propose a method for using the time-of-flight and anticoincidence systems for selecting γ rays from the background of charged particles in the γ-ray telescope. This method is based on measuring the time of flight of particles between the detectors of these systems. The proposed technique for selecting events by the time of flight provides a means for attaining a high detection efficiency for high-energy γ rays.

The proposed technique is considered as applied to the GAMMA-400 γ-ray telescope; nevertheless, it can also be used for other γ-ray telescopes with time-sensitive anticoincidence and time-of-flight systems.

SYSTEMS OF THE GAMMA-400 γ-RAY TELESCOPE

The GAMMA-400 γ-ray telescope [5, 6] consists of the following systems enumerated in the flight

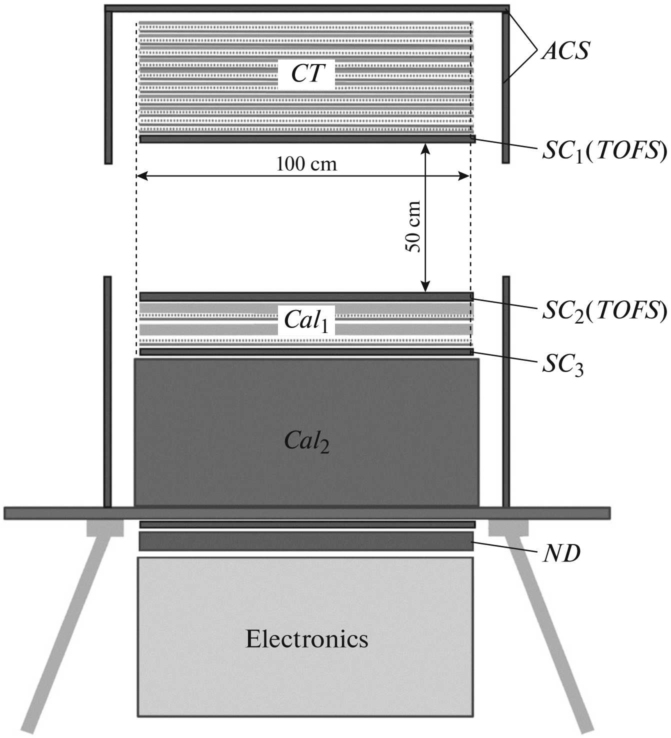

Fig. 1. Schematic diagram of the GAMMA-400 telescope: (*ACS*) anticoincidence system, (*CT*) converter–tracker, (*TOFS*) time-of-flight system, (SC_1, SC_2) TOFS scintillation detectors, (Cal_1, Cal_2) calorimeter parts, (SC_3) scintillation detector, and (*ND*) neutron detector.

direction of detected γ rays (from top to bottom, see Fig. 1).

The anticoincidence system (ACS) has been designed to reject charged particles that, while moving downward, trigger the ACS detector before triggering other systems. It is the anticoincidence system that is the object of investigation in this work, and its detailed description is presented in the next section.

In **the converter–tracker (CT)**, detected γ-ray photons generate electron–positron pairs in the conversion process. The particle tracks are recorded by ten pairs of strip detectors. The converter thickness is approximately the unit radiation length.

The time-of-flight system (TOFS) is composed of two scintillation counters SC_1 and SC_2 that have a high (0.6 ns) time resolution and are located at a separation of 50 cm. The TOFS is capable of determining the particle direction and estimating whether or not conversion of a γ ray occurred in the CT. The constructions of the TOFS and ACS detectors are similar.

The calorimeter (*Cal*) consisting of two parts Cal_1 and Cal_2 detects an electromagnetic cascade developed in it, which provides a means for measuring the energy of an incident γ-ray photon.

Scintillation detector SC_3 is intended for generating a trigger signal corresponding to an electromagnetic shower. **Scintillation detector SC_4** and **neutron detector *ND*** are used to separate hadronic and electromagnetic showers.

Let us consider the design and operating principle of the ACS in more detail.

ANTICOINCIDENCE SYSTEM

In the GAMMA-400, the ACS faces cover the converter on top and on each side. Each ACS face consists of two layers of parallel strips of scintillation detectors. The strips of one layer are displaced with respect to the strips of the other layer so that there are no rectilinear slits in the system. Each scintillation detector is a strip of a fast polystyrene-based scintillating material. The light picked off its both ends is detected by silicon pho-

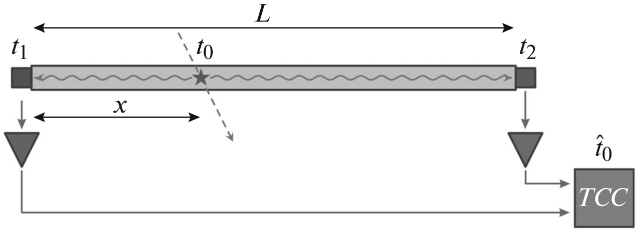

Fig. 2. Operating principle of the TCC circuit.

tomultipliers (SiPMs), which convert scintillation signals into electric pulses.

The SiPMs from both ends are connected to the time–coordinate compensation circuit TCC, which provides a means for determining the time of particle interaction with the scintillator material by compensating for the dependence of the scintillation detection time on the point of its origin [7].

The operating principle of the TCC is as follows.

Let us consider the scintillator strip with length L (Fig. 2). Assume that particle interaction with the scintillator material occurred at instant of time t_0 at distance x from its left end. If the effective longitudinal velocity of scintillation light in polystyrene is v (~0.5 the speed of light in vacuum), the left photodetector detects the scintillation at instant of time $t_1 = t_0 + x/v$. Light will reach the right end of the scintillator at instant $t_2 = t_0 + (L - x)/v$. Therefore, based on the response time of two photodetectors, we can determine the interaction time that is independent of x:

$$\hat{t}_0 = \frac{1}{2}\left(t_1 + t_2 - \frac{L}{v}\right).$$

This method is valid ($\hat{t}_0 = t_0$) in the case of a single interaction in the scintillator strip or under the condition that the time between scintillations from the second and first particles $\Delta t \geqslant |\Delta x/v|$, where Δx is the difference of the coordinates of the interaction points along the strip. In most cases of detection of a particle flying downward, this condition is satisfied for the ACS and SC_1 detectors, which are located at a large distance from the calorimeter.

In this study, we consider the top horizontal plane of the ACS.

BACKSPLASH EFFECT

A γ-ray photon originates an electromagnetic shower in the telescope. The major part of the shower is developed in the calorimeter. The higher the γ-ray energy, the larger the number of particles produced in the shower, in particular, those moving upward in the direction opposite to the direction of the detected γ-ray photon. The flow of such particles is called the backsplash [8]. It is mainly composed of γ rays with an energy of ~1 MeV. This flow, having a soft spectrum, "clogs" detectors located in the top part of the γ-ray telescope and simulates detection of a charged particle. Triggering of the ACS under the action of the backsplash disables detection of γ rays; at high energy, the detection efficiency falls down to zero. To solve this problem, we propose using the method for rejecting charged particles by the ACS response time.

TIME-BASED SELECTION TECHNIQUE

Let us consider the following event. A γ-ray photon crosses the ACS from top to bottom without interaction and produces an e^-e^+ pair in the CT. The pair continues moving downward. Charged particles generate a signal in scintillator SC_1 and, afterward, in SC_2 and hit the calorimeter in which they initiate an electromagnetic shower. The shower results in generation of the backsplash particles of which produce a signal in the ACS.

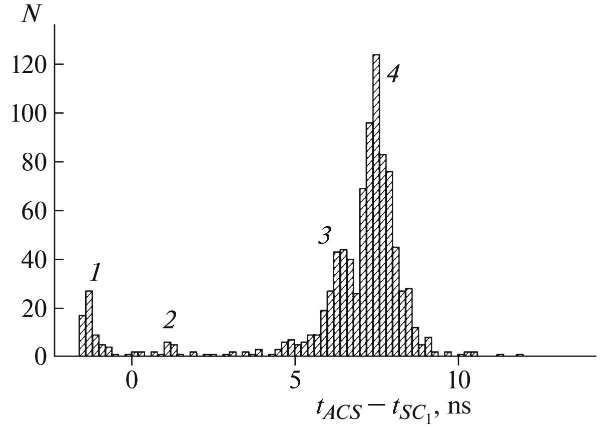

Fig. 3. Distribution of the difference of the ACS and SC_1 detector response times for γ rays: (*1*) γ-ray interaction in the ACS, (*2*, *3*, *4*) backsplash from the CT, Cal_1, and Cal_2, respectively.

If the γ-ray telescope detects a charged particle (in the direction top–down), the ASC is triggered as soon as the particle hits it, and a small delay is determined only by the time of light propagation in the scintillator. In the case of γ-ray detection, the signal is produced in the ACS a few nanoseconds later than the γ-ray photon is incident on it. The delay is explained by the fact that both the SC_1–ACS and calorimeter–SC_1 distances are ~50 cm; therefore, the time it takes for particles to reach the calorimeter, a cascade with the backsplash to be generated, and backsplash particles to return to the ACS is a few nanoseconds.

The ACS and TOFS detectors have time resolution $\Delta t \approx 0.6$ ns, as is shown in what follows.

Detection of a 100-GeV γ ray by the instrument was simulated using the Monte Carlo method. The shortest response time of the strips contained in the detector was assumed to be its response time. The response time of the strip was determined using the mathematical model of the TCC circuit.

Events were selected in which the detector signals indicated conversion in the CT. Based on selected events, the distribution of the difference of the response times was plotted for the ACS and SC_1 detectors (Fig. 3). Four peaks are easily discernible in the histogram:

– peak *1* (–1.5–0 ns) corresponds to γ-ray interaction in the ACS detector material;

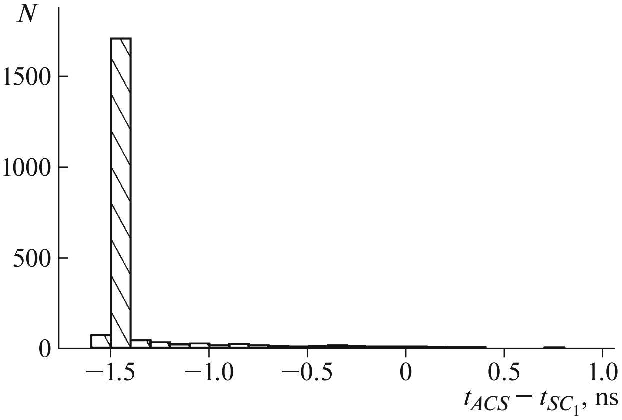

Fig. 4. Distribution of the difference of the ACS and SC_1 detector response times for protons (the horizontal scale is expanded).

– peak *2* (0–3 ns) is the backsplash from the converter;

– peaks *3* (4–7 ns) and *4* (7–10 ns) correspond to the backsplash from two calorimeter parts Cal_1 and Cal_2, respectively.

When a charged particle is detected, only the left peak remains in the histogram, since the ACS is always triggered first of all. This is demonstrated by the proton simulation result presented in Fig. 4. The nature of the "tails" is multiple interaction in the ACS (early backsplash or δ electrons). In these cases, the TCC method provides an underestimated time value: $\hat{t}_0 < t_0$.

The intrinsic time resolution of the ACS and SC_1 detectors has been ignored in the histograms. The histograms shown in Fig. 5 were obtained by smearing these data by the Gaussian kernel with standard deviation $\sigma = \delta t \oplus \delta t = \delta t\sqrt{2} \approx 0.85$ ns. A similar pattern is expected to be observed in our instrument. It is apparent that two classes of events differ widely, even being smeared.

The cumulative graphs (Fig. 6) show that, if the ACS detector is excluded from the anticoincidence circuit within time $t_{\rm th} \approx 3$ ns after the SC_1 triggering, events with the backsplash from the calorimeter are reliably identified and classified as γ rays. Calculations show that, at $t_{\rm th} > 2.9$ ns, the proton impurity in selected γ rays does not exceed 10^{-5}, the loss of useful events being 10%.

EXPERIMENTAL INVESTIGATIONS

The detector prototype has been experimentally investigated with the aim of determining the actual time resolution of the scintillation detector with SiPMs used as photodetectors.

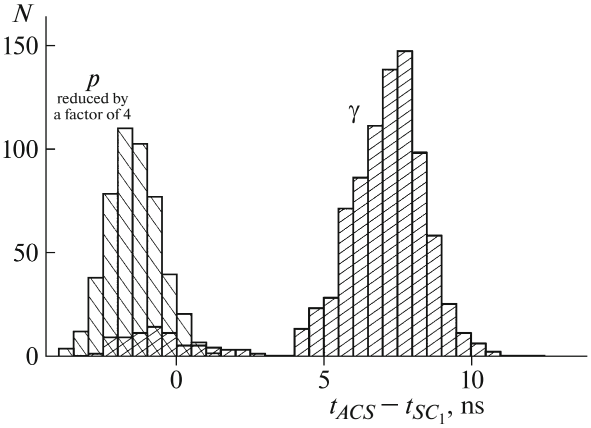

Fig. 5. Normal diffuse distributions for the difference of the ACS and SC_1 detector response times. The standard deviation of the smearing is equal to the Pythagorean sum of the ACS and SC_1 time resolutions. For ease of comparison, the heights of the "proton" histogram bars were reduced by a factor of 4.

The layout of the experiment is shown in Fig. 7. A SiPM (Hamamatsu MPPC S10985 100C) is attached to each end of the 35-cm-long scintillator strip. A collimated ^{90}Sr β source emitting 2.283-MeV electrons via compound nucleus ^{90}Y was placed near the side surface of the strip.

An XP2020 photomultiplier tube was placed opposite the β source to detect scintillations from a close distance. The photomultiplier tube produced the *Start* signal. The SiPM signals arrived at the TCC circuit, which generated the *Stop* signal. The time resolution—the full width at half-maximum (FWHM)—was determined by the distribution of intervals between the *Start* and *Stop* signals. The dependence of the time res-

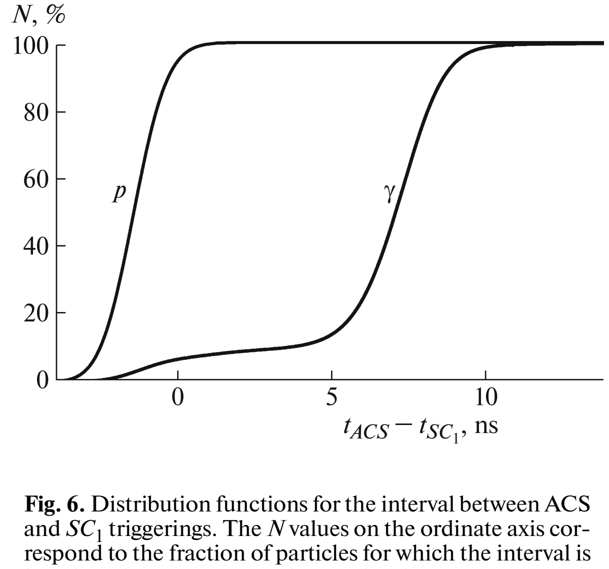

Fig. 6. Distribution functions for the interval between ACS and SC_1 triggerings. The *N* values on the ordinate axis correspond to the fraction of particles for which the interval is less than the respective *t* value on the abscissa axis. Events are presented both for protons and for γ rays.

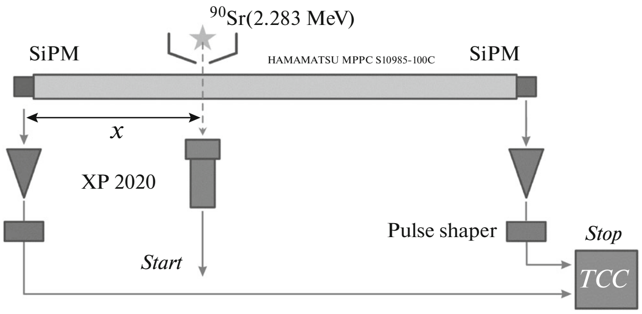

Fig. 7. Layout of the experiment with the detector prototype.

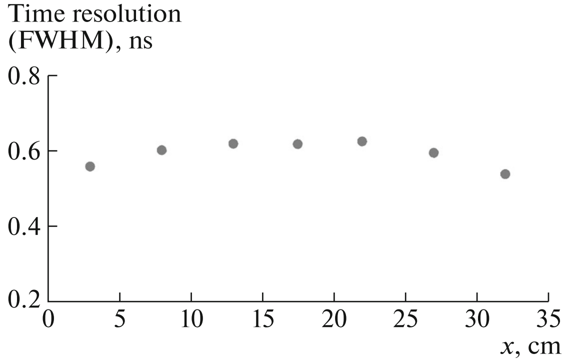

Fig. 8. Dependence of the time resolution on the source position.

olution on the distance from the source to the left end of the scintillator is shown in Fig. 8.

As a result, the time resolution of 0.6 ns has been attained. This value is adequate for effective selection of events accompanied by the backsplash from the background of events associated with detection of charged particles.

The possibility of designing detectors with a time resolution sufficient for implementation of this method was experimentally shown in [9].

CONCLUSIONS

The proposed method for using detectors with a high time resolution for discriminating events associated with detection of charged particles and high-energy γ rays generating the backsplash inducing the signal in the ACS makes it possible to select γ rays from charged particles (predominantly, protons) without substantial reduction of the γ-ray detection efficiency. The detection efficiency of the GAMMA-400 γ-ray telescope for high-energy γ rays is $\geqslant 90\%$. It has been experimentally shown that this method can be implemented with scintillation detectors using SiPMs for detecting scintillation signals.

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