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NUCLEAR EXPERIMENTAL TECHNIQUE

Calibrating the Prototype Calorimeter for the GAMMA-400 γ-Ray Telescope on the Positron Beam at the Pakhra Accelerator

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Abstract—A prototype of the electromagnetic calorimeter for the GAMMA-400 γ-ray telescope has been calibrated at the Pakhra S-25R electron synchrotron of the Lebedev Physical Institute. The measured energy resolution of the GAMMA-400 calorimeter is consistent with the results of the Monte Carlo simulation. The applicability of the Pakhra S-25R accelerator for calibrating detectors in various experiments has been confirmed.

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INTRODUCTION

The Russian space observatory with the GAMMA-400 γ-ray telescope is being created in accordance with the Federal Space Programs of Russia for 2009–2015 and 2016–2025. The GAMMA-400 telescope is designed to study high-energy γ rays with high angular and energy resolutions, obtain data on the nature of the dark matter in the Universe, and develop the theory of the origin of high-energy cosmic rays and particle physics [1–3]. The GAMMA-400 telescope has the best characteristics in comparison with the existing Fermi-LAT [4] and AGILE [5] satellite-borne γ-telescopes: high angular and energy resolutions of ~0.01° and ~2%, respectively, at a γ-ray energy of 100 GeV.

THE CALIBRATION OF THE ELECTRON (POSITRON) BEAM OF THE S-25R ACCELERATOR

Detector prototypes and detectors themselves for various experimental setups must be calibrated on charged-particle beams to verify the characteristics of the detectors and their tuning, to compare them with results of calculations, and to debug the software. The Pakhra S-25R electron synchrotron in Troitsk (Fig. 1) is now the sole permanently functioning Russian accelerator that generates electron and positron beams with energies of 100–500 MeV [6].

In order to perform a number of large-scale national and international projects in the fields of fundamental nuclear physics and astrophysics, a calibration channel of quasi-monochromatic secondary electrons (positrons) was created at the Pakhra accelerator of the Lebedev Physical Institute [6, 7].

The diagram of the calibration beam is shown in Fig. 2. The bremsstrahlung photon beam is generated by dumping an electron beam onto the internal target in the ring and, after leaving the accelerator chamber *1*, is formed by the lead collimator *2* with a 13-mm diameter hole. This collimator is located at a distance of 3.2 m from the exit flange of the accelerator. Further, the beam is transported through the air to the

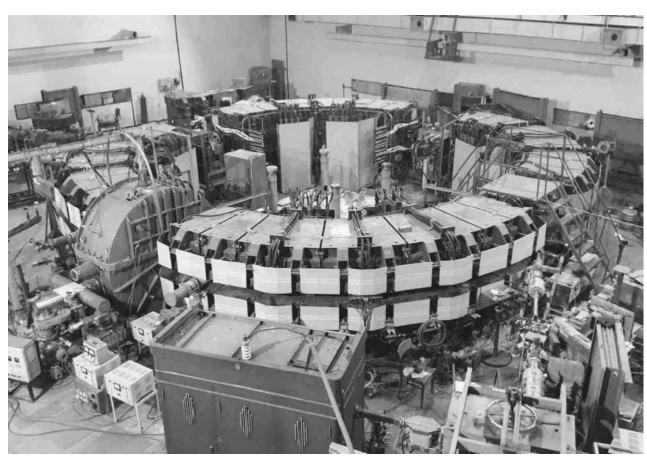

Fig. 1. The Pakhra S-25R electron synchrotron of the Lebedev Physical Institute (Troitsk).

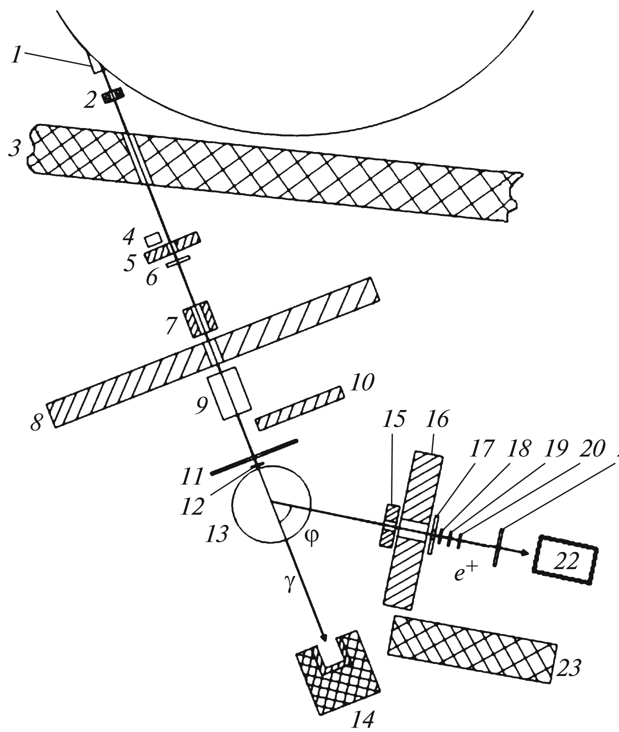

Fig. 2. A diagram of the calibration quasi-monochromatic beam of secondary electrons: (*1*) exit window of the accelerator chamber, (*2*) collimator, (*3*) concrete wall of the accelerator hall, (*4*) monitor of "stretching," (*5*, *7*, *16*) collimators, (*6*) beam monitor, (*8*) extended lead wall, (*9*) SP-3 cleaning magnet, (*10*) additional lead wall, (*11*) metal plate, (*12*) converter, (*13*) SP-57 magnet, (*14*) photon-beam absorber, (*15*) additional collimator in front of the main one, (*17*) scintillation veto counter, (*18–21*) scintillation counters, (*22*) calibrated detector, and (*23*) concrete block.

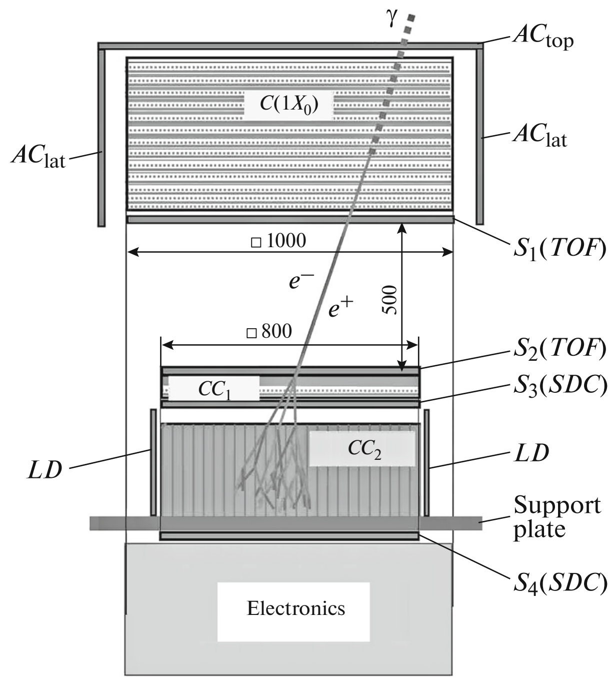

Fig. 3. A diagram of the GAMMA-400 γ-ray telescope: (*AC*) anticoincidence system (top AC_{top} and side AC_{lat} detectors), (*C*) converter–tracker, (S_1, S_2) scintillation detectors of the time-of-flight system (TOF), (S_3, S_4) scintillation detectors of the calorimeter (SDC), (CC_1) position-sensitive calorimeter, (CC_2) electromagnetic calorimeter, and (*LD*) lateral detectors (4 pcs.) of the CC_2 calorimeter.

converter *12*, which is located directly at the pole edge of the SP-57 magnet *13*. The positrons and electrons that emerge from the converter are separated in the magnet by their momenta. The secondary positron (electron) beam (depending on the direction of the magnetic field between the poles of the SP-57 magnet) is formed by collimators at angle $\varphi = 36°$ and is extracted by a system of scintillation counters *17–21* located along the trajectory of the electron (positron) beam behind the collimator *16*. Since the calibration beam of secondary positrons exhibits a lower background level compared to the electron beam, the positron beam was used to test and calibrate the prototype detectors of the GAMMA-400 γ-ray telescope. The scintillation veto counter *17* with dimensions of 60 × 90 × 10 mm and a hole diameter of 10 mm is used to form the positron beam and eliminate particles scattered from the collimator edges. Scintillation counters *18–21* are the trigger counters and are 15 × 15 × 1 mm in size. The position of the counters *17–20* relative to the collimator *16* is constant, while the position and size of the counter *21* depend on the calibration conditions for the tested detector. A laser located on a goniometric support is used to align the tested detector on the calibration beam relative to the beam trajectory.

The key characteristics of the quasi-monochromatic calibration positron beam used to calibrate the calorimeter prototype of the GAMMA-400 γ-ray telescope are as follows:

– the positron energy range, $E = 30–300$ MeV;

– the relative spread in the energies of the calibration beam at a positron energy of 300 MeV, a 10-mm diameter of the collimator *16*, and a copper-converter thickness of 1 mm, $\sigma \approx 5\%$;

– the intensity, ~20 e^+/s.

THE GAMMA-400 γ-RAY TELESCOPE

The GAMMA-400 γ-ray telescope, which has high angular and energy resolutions, is intended for the Russian space observatory, which will be launched into a highly elliptical orbit with an apogee of up to 300000 km [1–3]. Its main scientific tasks are:

– measuring cosmic γ-rays in the energy range from 20 MeV to 1000 GeV;

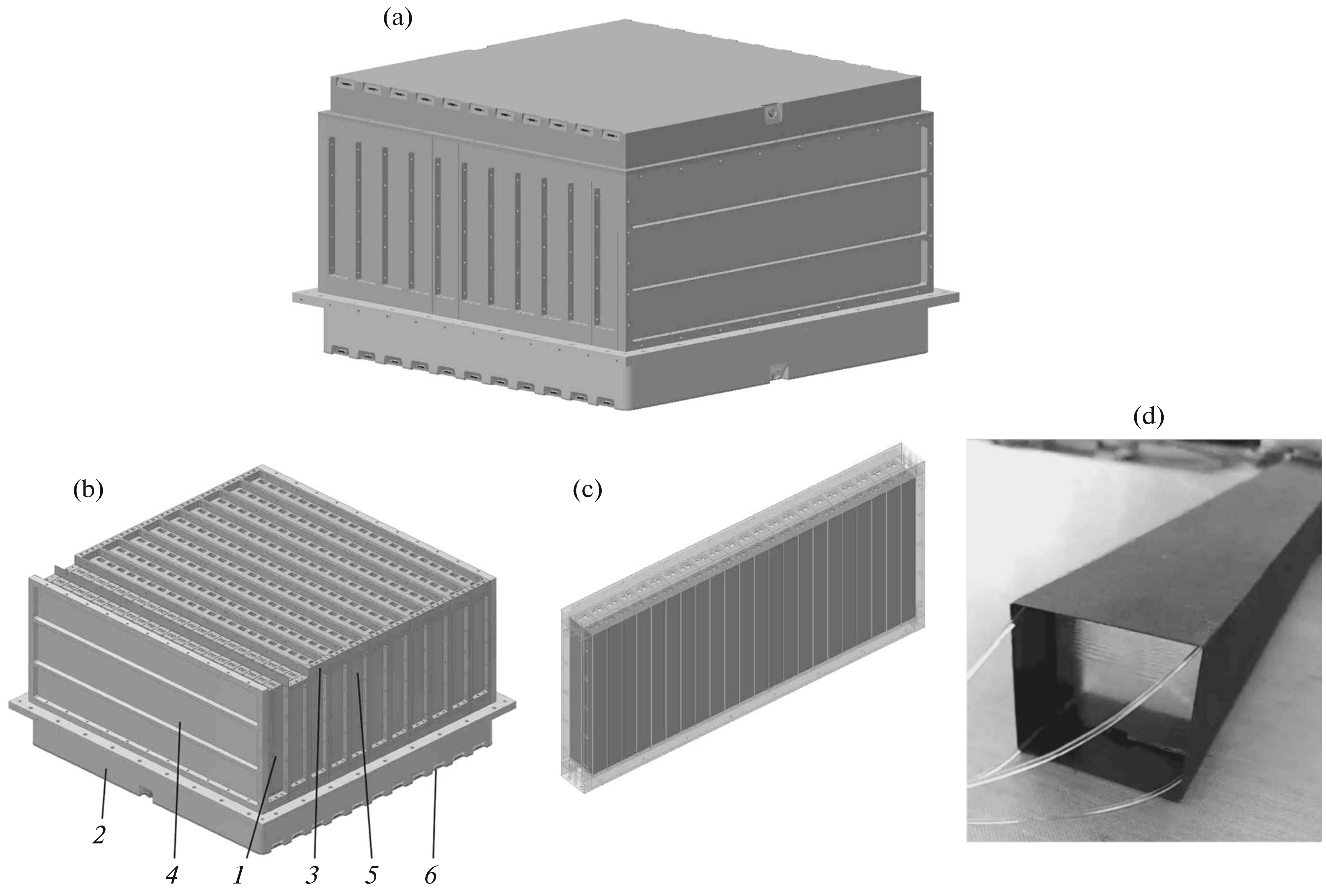

Fig. 4. The CC_2 calorimeter of the GAMMA-400 γ-ray telescope: (a) external view, (b) without the top and side lids, (c) carbon fiber cassette, (d) carbon fiber cell with a CsI(Tl) scintillator; (*1*) detector, (*2*) support grid, (*3*) clamping bar, (*4*) side panels of type 1, (*5*) side panels of type 2, and (*6*) bottom panel.

– detecting cosmic γ-rays and γ-ray bursts from active astrophysical objects of different nature (active galactic nuclei, blazars, pulsars, neutron stars, supernova remnants, black holes, red dwarfs, etc., as well as the Sun);

– searching for peculiarities in energy spectra from discrete and extended sources that can be associated with dark matter particles;

– detecting γ-rays from discrete variable sources in order to clarify the nature of particle-acceleration processes in these sources;

– carrying out detailed surveys and mapping of the Galactic plane, the center of the Galaxy, and extended sources with high angular and energy resolutions and high sensitivity;

– measuring the fluxes of cosmic-ray electrons and positrons.

The physical diagram of the GAMMA-400 γ-ray telescope is shown in Fig. 3.

The calorimeter, which consists of the position-sensitive CC_1 calorimeter with a thickness of $2X_0$ (X_0 is the unit of the radiation length) and the CC_2 electromagnetic calorimeter, is one of the main elements of the GAMMA-400 γ-ray telescope. The electromagnetic CC_2 calorimeter consists of 484 CsI(Tl) crystals; its thickness ranges from $13X_0$ to $16X_0$ for an electromagnetic shower along the symmetry axis of the crystal in the longitudinal direction (the final calorimeter thickness and the number of crystals will be determined after selecting the launch vehicle and specifying the mass of the scientific equipment). When particles from lateral directions are detected (using the CC_2 lateral aperture), the CC_2 thickness is $42.5X_0$.

In what follows, we will consider only the CC_2 calorimeter due to the particular complexity of its development, manufacture, and testing. The CC_2 calorimeter is an integrated structure (Fig. 4). It consists of a rigid aluminum case and carbon-fiber cells with 0.4-mm-thick walls, into which detectors based on CsI(Tl) scintillator crystals and SiPM silicon photodetectors are inserted. The total mass of the CC_2 calorimeter is 800–1000 kg (depending on the length of the crystals). The position of each crystal is fixed in space by a positioning structure, which determines the position of the

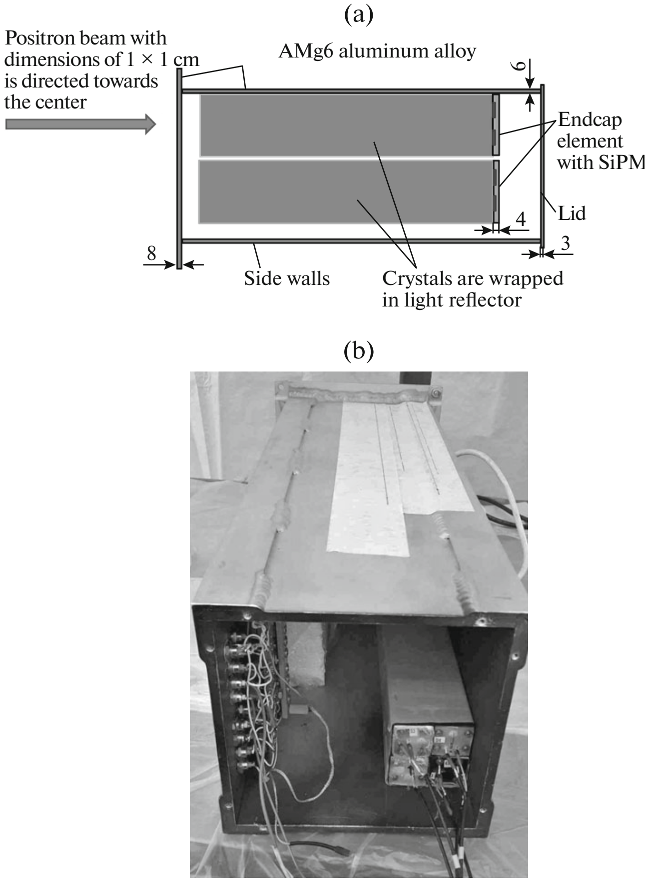

Fig. 5. The CC_2 prototype composed of four crystals: (a) diagram and (b) photograph.

crystals with an accuracy of ±200 μm or better. Carbon-fiber cassettes are used as a positioning structure. Each cassette contains two rows of crystal cells with 22 cells in each row. Cassettes are pulled together into a common block by clamping bars and are tightened by side walls, a support frame, and a lid. The calculations performed to determine the frequencies of natural vibrations and the stress–strain state showed that the design of the CC_2 calorimeter meets the requirements for the strength and rigidity.

THE PROTOTYPE CC_2 CALORIMETER FOR THE GAMMA-400 γ-RAY TELESCOPE

A prototype CC_2 calorimeter was produced for carrying out tests and calibrations. It is an assembly of four detectors based on CsI(Tl) crystals (Fig. 5); the dimensions of each crystal are 36 × 36 × 372 mm. The crystals are polished and wrapped in Tyvek. Two SensL MicroSB-60035-X13 SiPM photodetectors with dimensions of 6 × 6 mm are placed in optical contact with the end face of each crystal to register a scintillation signal. The detectors are located in a light-tight box made of aluminum alloy.

SIMULATION OF THE PROTOTYPE CC_2 CALORIMETER

Model calculations of the physical characteristics of the prototype CC_2 calorimeter for the GAMMA-400 γ-ray telescope were carried out with account of the processes of production, propagation, and detection of photons with optical wavelengths in CsI(Tl) scintillator crystals during the development of an electromagnetic shower from a monoenergetic positron beam. Optical photons produced in the CsI(Tl) scintillator are detected by a SiPM with a known efficiency and make their contribution to the output signal.

The simulation was carried out using the GEANT4 software package, in which the processes and models that characterize the cross sections and probabilities of particle-to-matter interaction processes were described using a standard set of PhysicsList libraries supplemented by the G4 OpticalPhoton library, which contains the characteristics of processes with optical photons and their processing procedures.

Simulation of scintillation materials and their characteristics for practical applications must be performed in view of the processes that occur during the excitation of scintillations (the light yield and its fluctuations), transmission of light in matter (absorption and scattering by density fluctuations or impurities), and interaction with the interfaces of media (reflection, refraction, absorption when photons pass from the scintillator into the photodetectors), as well as the characteristics and structure of the photodetector itself.

Taking these factors into account provides a chance to get as close as possible to the estimation of the real energy resolution determined by fluctuations in the light yield of a scintillation crystal, the loss of light in the material during its transmission to the photodetector, the influence of the contact between the crystal and the photodetector boundaries and the boundaries of the crystal itself, and the efficiency of absorption in the light photodetector.

The above-described diagram of the CC_2 prototype was used in the simulation. Figure 6 shows a schematic diagram for the simulation of the CC_2 prototype with the arrangement of its axes and the SiPM photodetectors in the geometry when the positron beam is incident along the normal to the end face of one of the crystals. The aperture of the plane-parallel monoenergetic positron beam with energies of 100, 200, and 300 MeV was limited by an area of 10 × 10 mm^2, and the distribution of particles in it was uniform.

The CsI(Tl) crystals (see Fig. 6) are designated as sensitive volumes with numbers 1, 2, 3, and 4. The total energy deposited inside them and the number of photons produced both by scintillations with a light yield of 54 photons/keV and by Cherenkov radiation. The positron beam hit the center of the end face of corner crystal 4. As mentioned, two 6 × 6 mm SiPMs

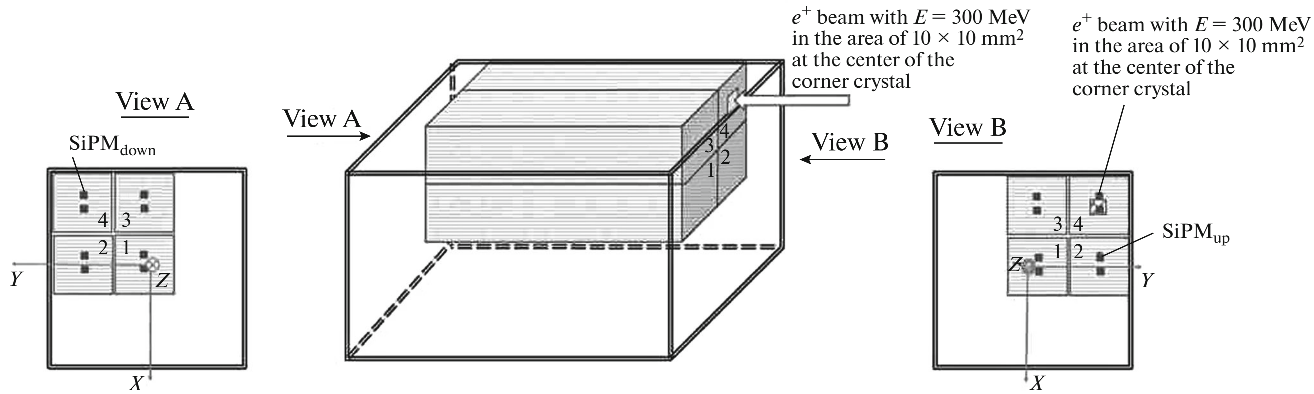

Fig. 6. A diagram of the CC_2 prototype used in the simulation.

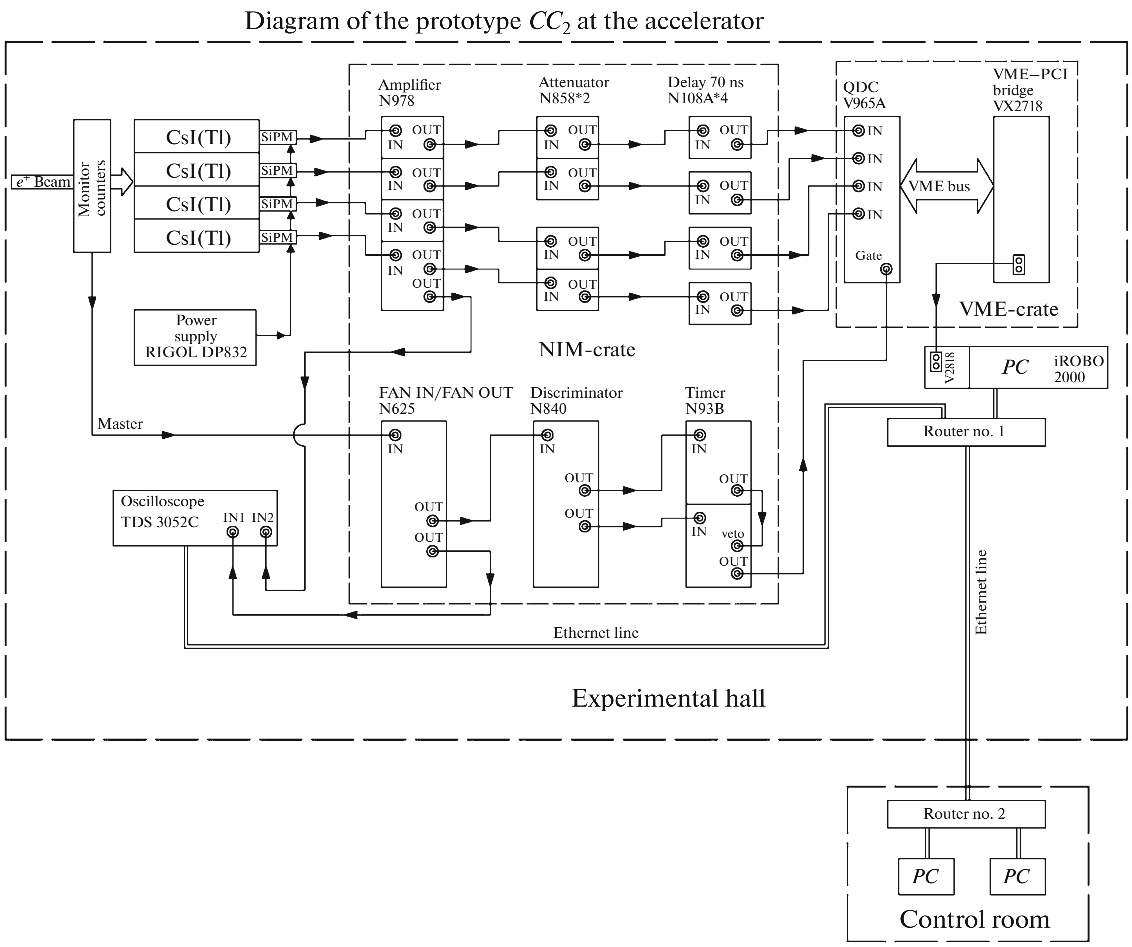

Fig. 7. The set of measuring equipment for calibrating the prototype: (RIGOL DP832) power supply, (Tektronix S3032C) digital oscilloscope, (Tektronix AFG3022C) generator, (NIM) crate with N8301/60 power supply, (N978 CAEN) fast amplifier, (N840 CAEN) leading edge discriminator, (N108A) delay, (N858 CAEN) dual attenuator, (N93B CAEN) dual timer, (VME) crate with VME8200 power supply, (V965A CAEN) QDC, (PC) PC iROBO 2000 personal computer with software for QDC operation, and (VX2718 VME–PCI bridge) VME–PCI optical link bridge.

Table 1. Effect of the converter thickness on the energy resolution of the positron beam at an energy of 300 MeV

Cu converter thickness, mm	Energy resolution σ of the positron beam in view of the CC_2 resolution, %	Positron beam intensity, Hz
3	10.0	17
1	10.1	16
0.1	10.0	7.2
Without the converter (conversion on air molecules)	9.8	7.0

were attached to the end faces of the crystals. Each of them forms an optically transparent surface of contact with the crystal with an area of 6 × 6 mm^2. Photons incident on this surface are detected in accordance with the characteristics both of a SiPM as an optical volume (a refractive index and an absorption length) and of the contact boundary (a reflection coefficient and a quantum efficiency).

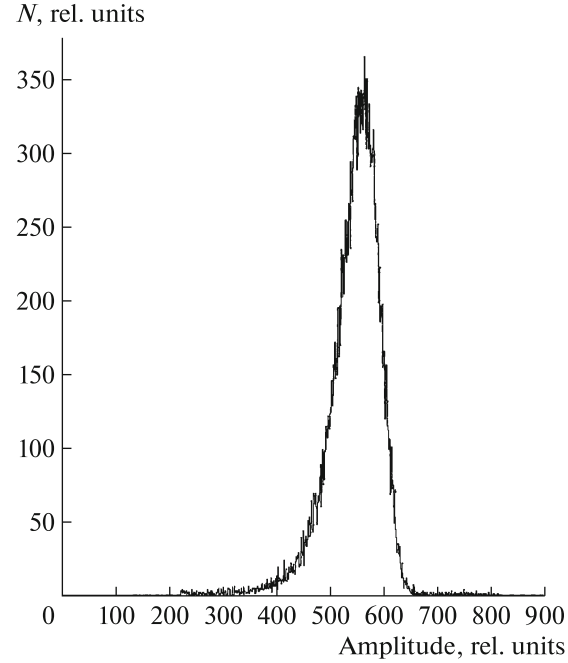

Fig. 8. An example of the distribution obtained under irradiation with a 300-MeV positron beam.

CALIBRATION OF THE CC_2 PROTOTYPE CALORIMETER ON THE POSITRON BEAM

The CC_2 prototype of the GAMMA-400 γ-ray telescope was calibrated using a beam of monoenergetic positrons with an energy of 100–300 MeV. The diagram of the CC_2 prototype on the beam is shown in Fig. 2. The set of measuring equipment used for the calibration is shown in Fig. 7.

A remote access system was used to provide communication between the set of measuring equipment in the experimental room and the control room. This system consisted of router 1 in the experimental hall, to which network devices of the measuring equipment set (an oscilloscope and a personal computer) located here were connected, and cables that connected routers 1 and 2 in the control room where personnel worked during the operation of the accelerator. Router 2 is connected to a server with Internet access.

The parameters of the electronics were selected before the calibration: the attenuator coefficient, the gate width of the charge-to-digital converter (QDC) with account for the parameters of the particle detection signal, and the delay time.

The first stage of the calibration consisted in investigating the influence that the thickness of the converter *12* (see Fig. 2) had on the energy resolution of the positron beam at an energy of 300 MeV. The results of the investigation are presented in Table 1. It is seen that the copper-converter thickness has practically no effect on the energy resolution of the beam. Subsequently, during the calibration, a 1-mm-thick copper converter was used.

At the second stage of calibration of the CC_2 prototype, its energy characteristics were investigated at positron-beam energies of 100, 200, and 300 MeV. An example of the distribution obtained by irradiation with a 300-MeV positron beam is shown in Fig. 8. It was established that the energy resolution of the calorimeter prototype obtained by irradiation with a positron beam and the results of the model calculations of its physical characteristics coincide within the measurement accuracies (Fig. 9). The energy resolution of the model at a positron energy of 300 MeV was 10%.

CONCLUSIONS

During the calibration of the CC_2 prototype calorimeter for the GAMMA-400 γ-ray telescope, the energy resolution of the prototype on CsI(Tl) scintillators was measured. The measurement results showed that the energy resolution is no worse than 10% at a positron energy of 300 MeV.

The characteristics of the CC_2 prototype calorimeter of the GAMMA-400 γ-ray telescope, which were investigated on the calibration positron beam of the Pakhra S-25R accelerator, agree within the measurement accuracy with the results of the Monte Carlo simulation.

The applicability of the Pakhra S-25R electron synchrotron (Lebedev Physical Institute, Troitsk) to calibration of detectors in nuclear physics equipment,

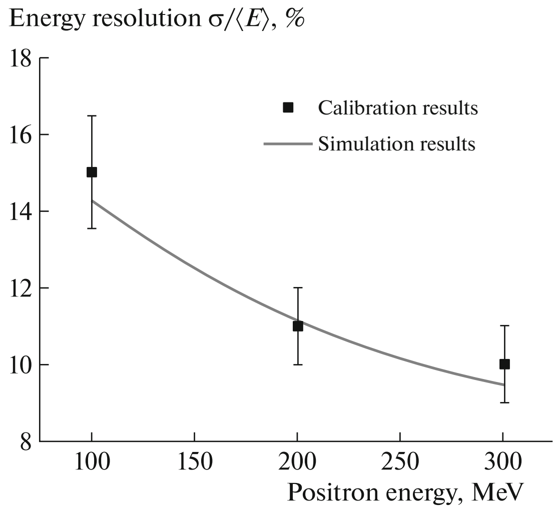

Fig. 9. The energy resolution of the CC_2 calorimeter prototype: the simulation results are presented by the curve, and the calibration results are shown with points.

including devices for space research, has been confirmed.

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