Proceedings of ICRC 2001: 3030 © Copernicus Gesellschaft 2001

ICRC 2001

Stabilized 0.3–2000 MeV gamma-ray specrometer for satellite mission "CORONAS-PHOTON"

YU. D. Kotov, V. N. Yurov, V. T. Samoilenko, and I. V. Rubtzov

Astrophysics Institute of Moscow State Engineering Physics Institute

Abstract. A γ-ray spectrometer in an energy range of 0.3-2000MeV based on CsI(Tl) single crystals with a total area of 32 x 36 cm^2 and 18 cm thickness is described. A modular structure of the construction allows for logics optimization of the selection of valid events, effective background suppression, and appreciable extension of the operating range of the counting rate of γ-events. A fast system for stabilizing the energy scale by a pulse light source and a slow stabilization-calibration system with the use of a source of "tagged" γ-quanta are employed. Pulse shape discrimination is used for separation of events produced by gamma-ray and neutrons. Plastic scintillators are used to eliminate charge particle background. An energy resolution of (9.9±0.1)% at 0.662MeV and a time resolution for coincidence and anticoincidence of 0.1μs are obtained.

1 Introduction

A satellite experiment "CORONAS-PHOTON" (Kotov at al., 1995) for study of solar radiation in wide energy band includes high energy radiation spectrometer NATALYA-2M. The short description of the mission status is given in report of Kotov et al (2001). HATALYA-2M The technological model of NATALYA-2M instrument is readied and currently putting to the tests at the Institute of Astrophysics of Moscow State Engineering Physics Institute.

2 Instrument description

The detecting unit of the spectrometer (Fig. 1) consists of a set of scintillation counters (SE_1 SE_2, ACD, and ACC). A spectrometer (SE), based on assembly of CsI(Tl) crystals with a total area of 32 x 36 cm^2 and a total thickness of 18cm. It consists of two sections (SE_1 and SE_2) positioned above the other. is employed for γ-radiation. The events initiated by the incoming charged particle are rejected by plastic scintillation detectors (ACD and ACC) that fully surround the section SE_1 and covered from the top the section SE_2. The spectrometer has a modular structure. It consists of 16 modules of separated crystals of 360 x 80 x 45mm dimensions, each of it is viewed by two PMT 110-type photomultipliers from opposite sides. Preamplifiers (PA) are placed directly on PMTs and have two outputs: H K_a=1 (H - high energy output) and K_a=25 (L - low energy output).

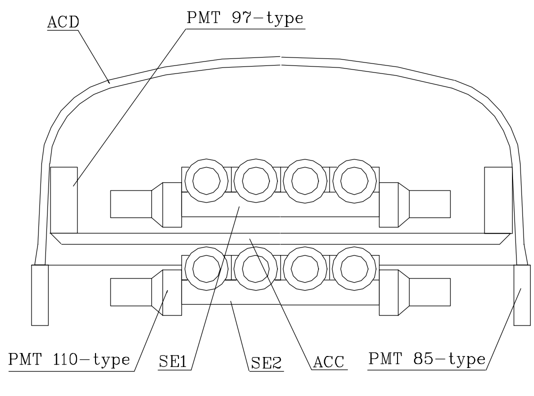

Fig. 1. Detecting unit of the NATALYA-2M spectrometer.

The modules are placed in two layers (four modules in each one). The energy band of the spectrometer is 0.3MeV-2 GeV. To prevent high counting rate latching and reduce upward background the total band is divided into four ranges, in which detection of radiation proceeds in the following manner.

Hard X- and low-energy γ-rays (R-range) of 0.3-2.0MeV. The signals (A_1 – A_4) from modules of the first layer of the

Correspondence to: Yu.D. Kotov (kotov@axpk40.mephi.ru)

upper section are used in measurements. The L-outputs signals from PMT of each module are summed and then, after being amplified, they arrive at individual analog-to-digital converters (ADCs), allowing to increase the acceptable counting rate. The signals from the ACD and ACC counters and first-layer modules of the lower section (C_1-C_4) of the spectrometer are switching in anticoincidence, making it possible to reduce the background of charged particles and albedo γ-rays.

Low-energy γ-rays (L-range) of 1-10MeV. Eight modules of the upper section of the spectrometer are employed for the measurements. The signals from the L-outputs of all modules (A_1-A_4 and B_1-B_4) are summed and yield to the ADC. The signals from the counters ACD, ACC and second-layer modules (D_1-D_4) of the spectrometer's lower section are connected in anticoincidence in similar manner to R-range operation.

Medium-energy γ-quanta (M-range) of 7-200MeV. Modules of both sections of the spectrometer are used for measurements. The signals from the H-output are summed and yield to the ADC. Only the ACD signal is switched in anticoincidence.

High-energy γ-quanta (H-range) of 100-2000 MeV. The detection is similar to that of the M-range.

Events in the ranges are selected by using additional information on the energy releases (E,MeV) in spectrometer layers and anticoincidence detectors.

1. For M-range:

$$(EA>5 \vee EB>5)\cdot(ED<60)\cdot(E_{sum}<200) \quad (1)$$

2. For H-range:

$$(E_{sum}>70)\cdot((5<EA<200)\cdot(EB>15)\cdot(EC>)\vee (EB>15)\cdot(EC>5)\ (ED>5)) \quad (2)$$

By telecommand the anticoincidence threshold for layers D and C can be select as 0.3 or 1MeV as well as threshold of anticoincidence signals from ACD and ACC can be changed by four steps from 0.3 to 1MeV or these signals can be canceled separately.

The use of several PMTs imposes rather stringent requirements on equalizing gain factors and temporal stability of optical contacts. Moreover, the PMT gain is known to be dependent on its average current, which changes greatly under the variation of the average energy release in the detector. Our laboratory measurements that imitated the action of solar flares on the instrument have shown that due to change in the average energy release in the detector during typical solar events the gain falls typically by 5% and up to 15% for high-power flares. Measurements that imitate the passage by a satellite the region of the South Atlantic magnetic anomaly at height 500km have shown that the gain change may reach 8% while the recover time is 30 min.

In order to compensate these effects in the spectrometer a system for stabilizing of the spectrometric channels is used. It designed in the following manner: in each layer there is a reference source of light pulses based on a pulse current generator (RG) and a light-emitting diode (LED). Light from LED is split by optical fibers and then injected to the middle point of the large face of each module. The stabilization boards of each PMT measure the signal corresponding to the reference pulse and change the voltage at the PMT dividers in such a manner that the signal amplitude remains constant. The signal frequency is 1kHz, and the feedback time constant is ~3sec. Measurements with the stabilization system revealed that it reduces the spectrometric-channel instability to 0.1%. The temperature dependence of the CsI(Tl) light output and LED light output are compensated by adjusting the RG current in response to the temperature sensor.

A radioactive α-source is installed on the crystal surface of one module of the upper layer of the CE_1 spectrometer section for calibration the energy scale and monitoring the factor of neutron-gamma separation during the flight. However, due to change of the surface quality and different temperature dependence's of the CsI(Tl) light output at different ionization densities, the calibration of the α-source line may be insufficiently accurate for gamma-ray spectrometric measurements. This problem was solved by introducing into the spectrometer of additional calibrating γ-source in the form of a plastic scintillator with dissolved ^{60}Co isotope. The ^{60}Co decay scheme is such that 100% of γ-quanta are accompanied by β-particles with an average energy $\bar{E}_\beta$ =96keV, thus permitting the creation of a tagged γ-quanta source. The plastic scintillator is viewed by an individual PMT type-85, whose signal after passing an amplitude discriminator-shaper is employed as the tagging signal. An additional ADC, which processes signals of the L-range and operates in coincidence with the tagging signal is included in the recording system for obtaining calibration spectra. In order to improve the time resolution of the selection circuits, a constant-fraction shaper is employed as an input discriminator. Measurements with a time-to-digital converter have shown that the time locking accuracy is -20ns. This makes possible to set the time resolution (0.1 μs) of the coincidence and anticoincidence circuits (the miscount probability is within 0.01) and to efficiently suppress the background at high counting rates.

The light output of LEDs may change in time due to degradation. The design features of the spectrometer lead to the necessity of using a separate LED and generator for each layer. It may result in a mismatch between the energy scales of different layers and, as a result, impaired energy resolution. Moreover, satisfactory thermal compensation is not attained in the operating temperature range (from -5 to +45°C), and the temperature instability of the spectrometric channel may reach ±3%. To eliminate the temporal and temperature instabilities a second (slow) automatic control circuit was introduced that is utilized signals from the calibrating radioactive source. The comparison circuits set up in each layer and synchronized by the same signal as the calibrating ADC, adjust the amplitudes of the LEDs so as to maintain the position of ^{60}Co lines constant. The control time constant is ~300sec, the stabilization accuracy is better 1%, and the range of full compensation for the scintillation amplitude change within factor from 0.5 to 2.

3 Results

The use of scintillator of that size and configuration requires special attention to provide the best light-collection conditions; that is why the properties of modules with various reflector and optical contacts were studied. Characteristics of three versions of the module design were investigated. The longitudinal nonuniformity of the light collection coefficient and energy resolution for ^{137}Cs (662 keV) was studied. The behavior of this the light collection coefficient is properly described by the function

$$K(x) = A\cdot(\exp(-(l_0/2-x)/\lambda)+\exp(-(l_0/2+x)/\lambda)), \quad (3)$$

where x is the distance from the module center, A is the dimensional factor, l_0 is the module length, and λ is the light attenuation length. The most advantageous design provides the highest energy resolution (11.7%) and minimum nonuniformity (~1%).

Data on energy resolution were obtained by using an amplitude-to-digital converter (ADC) and a shaping circuit based on 2μs RC-time constant. CsI(Tl) emits scintillation with two fluorescence components with decay constants of ~0.7 and ~7μs, which have almost equal intensities for relativistic particles. As the integration time increases up to 10-15μs, the energy resolution is improved, but the effect of impulses superposition leads to an impaired energy resolution and spectrum distortions at counting rates slightly exceeding the background. For example, even at an integration time constant of 2μs, the results presented above were obtained with a counting rate ($E_\gamma > 0.1$ MeV) close to the background (1-2) x 10^3 pulses/s), and if the counting rate increases by an order of magnitude, the energy resolution deteriorates (16%), and a pronounced superposition peak arises (~2% of the main peak). Therefore, it was proposed to use a weakly integrated signal (τ~0.4μs) for trigger operation (threshold, coincidence-anticoincidence, etc.) and τ~10μs integrated signal for spectrometric measurements. The ADC is equipped with a highly efficient zero-line restorer and superposition suppression circuits. The energy resolution was measured in energy range from 0.511 to 2.62MeV for the module design no.3 by using such parameters. The dependence of the resolution on energy agrees well with the expression:

$$A/(E_\gamma^{1/2})+B, \quad (4)$$

where E_γ is the energy of γ-quanta, A is the dimensional factor, and B is the detector inhomogeneity. The value of B ~1% indicates the prevailing contribution of the statistical fluctuation of the number of photoelectrons. The use of the ADC design proposed allowed us to reach an energy resolution of 9.9 ±0.1% at an energy of 0.662MeV without observing an impairment of the resolution and spectrum distortions at a counting rate of up to 3 x 10^4 pulses/s.

Evaluating the effectiveness of the slow circuit was carried in the next manner: a sharp change in the LED properties was imitated by switching the RG circuit. The change in the energy scale was monitored by the variation of the position of the reference α-source line, and spectra were recorded once a minute. The results (Fig. 2) show a reaction of slow stabilization system .

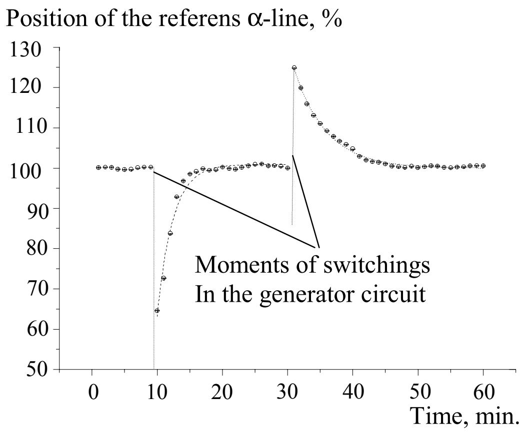

Fig. 2. Response the slow circuit of the automatic control system to a parturbation.

To evaluate the selection efficiency of "tagged" system, we performed measurements with the CE technological module and a laboratory prototype of the source of tagged γ-quanta, which was prepared on the basis of a ^{22}Na source from an standard γ-sources set and a pure plastic scintillator. The calibrating source was placed 55cm above the module center, and ^{137}Cs and ^{60}Co sources from the same set were located at the module case. In this case, the counting rate was near to 36 kHz for the threshold $E_\gamma > 0.1$ MeV. Figure 3 shows the energy-release spectra for regimes with coincidences switched off and on. In the former case, the counting rate for a line of 0.662MeV reaches 700 Hz/channel, and the lines of the ^{22}Na source are not resolved. When coincidences are switched on, the background and both high-power sources are well suppressed (the 0.662-MeV line—by a factor of 10^3).

Hence, this technique allows to make a calibration of the system under arbitrary background conditions and provides a reliable absolute correspondence of the spectrometric channel of the NATALYA-2M to the energy scale.

As the slow stabilization system guarantees limiting range (50-200 %) of LEDs amplitude regulation it is necessary to know the possible temporal degradation of LEDs pulse. The results of observation of long duration stability are shown on fig. 4. The solid line is an approximation of the

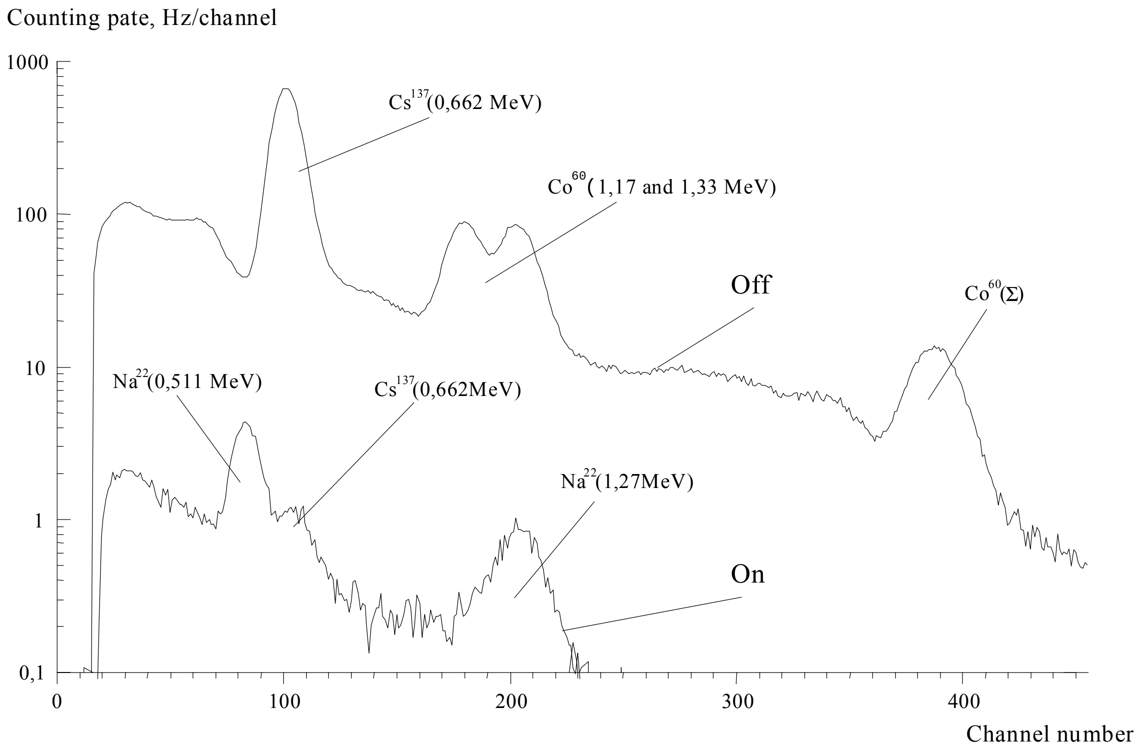

Fig. 3. Calibrating pulse-height spectrum for switched on and off coincidence.

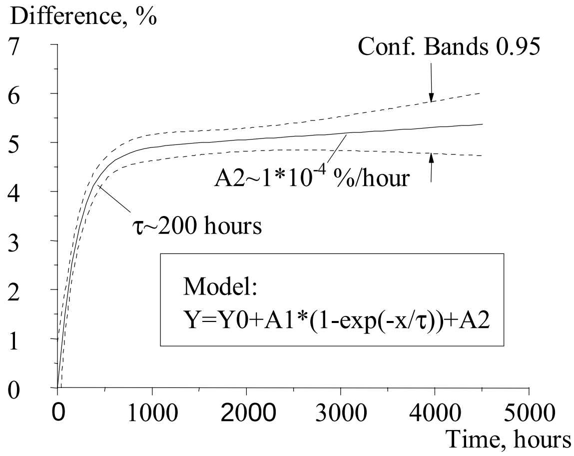

Fig. 4 The temporal dependence of difference between measuring and original values of energy scale.

experimental data. The temporal dependence of the difference between measuring and original values of energy scale is existing. This value is inversely proportional the change of the LEDs amplitude. It is seen, that during ~500 hours the difference increases exponentially on ~5% and then linearly with coefficient 10^{-4} %/hour. It is ~10-15% for the mission operation time. Hence, the slow stabilization system will guarantee the energy measuring accuracy not worse then 1%.

4 Summary

The undertaken measures allowed appreciably improve the energy resolution of the NATALYA-2M device and will ensure operation of a long-term autonomous experiment with stable metrological provision in wide ranges of varying temperature conditions and background counting rates.

References

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