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Numerical Simulation of Metrological Characteristics of Cosmic Radiation Detectors

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Abstract—In this paper, we describe the methods and results of mathematical simulation of the interaction between cosmic rays and detectors. This has increased the accuracy of determining the level of radiation impact on materials and components of spacecraft. The application of the results obtained in the design and production of advanced spacecraft will significantly increase the reliability and extend the service time under the cosmic radiation exposure.

Keywords: cosmic rays, semiconductor detector, calibration, event selection, mathematical simulation
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INTRODUCTION

Increasing the service time of spacecraft and the widespread use of elements sensible to radiation exposure in their construction make it urgent to require control of radiation conditions in orbiting spacecraft.

Nowadays, in order to evaluate radiation conditions at orbit, one uses the models of spatial energy distributions of proton and electron fluxes in the Earth's radiation belt (ERB) for the periods of solar maximum and minimum on the basis of measurement results. The most known international models AE8 and AP8 are intended to describe electron and proton fluxes, respectively [1, 2]. It should be noted that both of these models are constructed on the basis of limited and considerably outdated experimental data arrays obtained during the 1960s–1970s.

However, real fluxes of energetic charged particles of ERB can differ substantially (by a few orders of magnitude) from simulated values. This is explained by the fact that particle fluxes have very considerable long-term (months) variations as well as the short-term (days, weeks) ones related to the changes in the solar and geomagnetic activities which were not taken into account in the existing models of the ERB. This is valid also with respect to the other components of cosmic radiation, still more irregular ones, such as solar cosmic rays.

Therefore, the most reliable way to determine real radiation conditions of spacecraft exploitation is carrying out measurements of the fluxes of particles affecting equipment by means of using instruments installed in the spacecraft in question or in other spacecraft operating in the close orbits.

In order to provide such measurements, in many cases, one uses instruments in which the registration of electrons and protons is carried out by means of detectors combined in telescopic systems [3]. Such detecting systems consisting of detectors of various types situated successively along one longitudinal axis are widely used in space instruments intended to detect electrons and protons of the ERB and also the particles of solar and galactic cosmic rays.

The interpretation of instrument readings is carried out on the basis of laboratory instrumental calibrations of detecting systems. However, the information obtained with use of calibrations is insufficiently complete, since it is impossible to reproduce in laboratory experiments the energy and angular distributions characteristic of the charged particle fluxes in space.

When a flux of charged particles passes through detectors, the energy losses of single particles may have fluctuations owing to the statistical nature of the ionization process. In addition, statistical fluctuations of electron specific energy losses in detection are significantly more than those of protons, since the mass of electrons is less than that of protons. Therefore, to achieve a required accuracy of measurements, it is necessary to use numerical calculations of energy release in detectors.

The aim of this study is a numerical simulation of the interaction between detectors and fluxes of electrons and protons which would allow improving the accuracy of determining metrological characteristics of telescopic detecting systems.

CALCULATION METHOD

Let us consider the calculation method by example of a real telescopic spectrometer of protons and electrons (SPE) with characteristics described in [4]. The principal element of SPE is a detection unit (DU) consisting of several semiconductor detectors (SCD) of different thicknesses and a scintillation detector. All the detectors are fixed one under another along one axis. This spectrometer makes it possible to detect separately the flux of protons and electrons within quite a narrow range of incident particle energy release. The model of the investigated telescopic system is shown in Fig. 1.

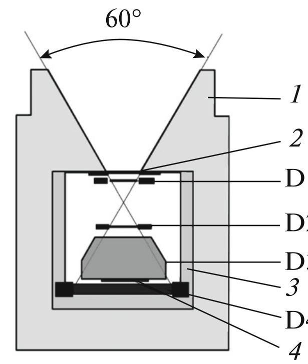

Fig. 1. Model of the investigated detection unit: (*1*) is the instrument body; (*2*) is foil; (*3*) is plexiglas; (*4*) is a photodiode; D1–D4 are detectors.

Before the detectors, there is a collimator with the opening angle equal to 60°. The first SCD (D1) with thickness of 0.04 mm is protected by foil having thickness equivalent to 10 μm of silicon. The thickness of the second SCD (D2) is 0.5 mm, the third detector (D3) is a CsI scintillator with thickness of 10 mm, and the fourth detector (D4) is also a SCD with thickness of 1 mm. Between D3 and D4, there is a photodiode with the equivalent thickness equal to 300 μm of Si which transforms the light flashes from passing particles into electrical pulses. The side walls of the detecting unit body consist of a 10-mm-thick layer of brass and a 5-mm-thick layer of plexiglas.

The calculations of the electron and proton energy loss values in the elements of the DU were carried out for the three-dimensional model with isotropic incidence of electrons and protons with the help of the software toolkit GEANT4 [5]. The data were used in order to simulate the operating of electronics of SPE in the Simulink environment (MATLAB) [6].

Simulation of the interaction between charged particles and elements of the telescopic system took into consideration ionization processes, including the secondary electron generation, bremsstrahlung, and multiple Coulomb scattering. The simulation of the electromagnetic interaction processes were carried out with using the library package Livermore [7]. The processes of nuclear interactions occurring when protons pass through the telescopic system were taken into account with the help of a standard library QGSP_BIC_HP [8]. The calculations of electron and proton energy losses in the elements of the DU were performed on the Lomonosov supercomputer of Moscow State University [9].

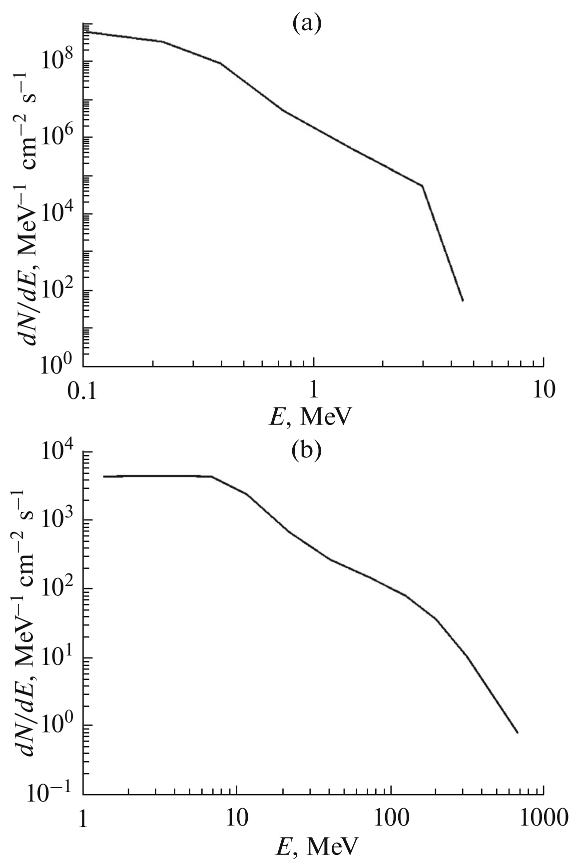

Fig. 2. Initial differential spectra of (a) electrons and (b) protons at the circular orbit of 1700 km with $L \sim 1.4$ used in the calculation with the help of GEANT4.

In order to provide analysis of the instrument operation, we used energy spectra of electrons and protons obtained with the help of the AE8 and AP8 models for several specially selected orbits at which the radiation monitoring data give the possibility to predict radiation conditions for a large number of spacecraft orbits [10]. In Fig. 2, one can see the differential particle spectra for a circular orbit with altitude of 1700 km and inclination of 77° at which the geomagnetic field parameter value $L \sim 1.4$. For each spectrum, the calculation was carried out with use of data of 10^8 events (incident particles). This made it possible to collect sufficient statistics of signals for the upper energy channels (above 4 MeV for electrons and above 100 MeV for protons).

Energy ranges of measured energies of electrons and protons in SPE

Electron channel number	E1		E2	E3	E4	E5	E6	
Range limits, MeV	0.15–0.35		0.35–0.6	0.6–1.0	1.0–2.0	2.0–4.0	4.0–10.0	
Proton channel number	P1	P2	P3	P4	P5	P6	P7	P8
Range limits, MeV	2.0–4.0	4.0–9.0	9.0–15	15–30	30–53	53–100	100–160	≥160

RESULTS AND DISCUSSION

The SPE contains electronic logic devices of selection operating on the basis of the principle of coincidence and anticoincidence of pulses. They allow one to obtain energy distributions (the dependence of particle flux on their energy) of electrons and protons in space and time for several energy ranges. The energy range limits were chosen as follows: six nearly logarithmically spaced energy ranges for electrons with energies of 0.15–10.0 MeV and eight energy ranges for protons with energies of 2–160 MeV and above (see table).

The calculated data contain information about the energy of initial particles (electrons or protons), values of energy release in each detector with energy losses of secondary particles taken into account, and incidence angle of a primary particle, as well as information indicating whether the initial particle has passed through the collimator of the instrument.

In the case of the isotropic distribution of the incident particle flux, it is possible to register particles having passed through the body of the instrument by separate detectors. Thus, in the case of registration of electrons, one may obtain a considerable increment of events in D3 (scintillator) owing to the registration of bremsstrahlung gamma-ray quanta having been generated inside the instrument body (Fig. 3a). Such events should be excluded from the analysis. So for the further analysis of detected electrons, we used the events with nonzero energy release in D2 (let us designate this selection criterion as strobe-1), which makes it possible to exclude almost completely the signals from the particles having passed out of the collimator (Fig. 3b).

The same principle was used for protons. However, in the case of registration of energetic protons with the track length exceeding the thickness of side walls of the instrument body (80 MeV), extra event registration is possible owing to the registration of the particles having passed out of the collimator. In order to exclude such a possibility, this criterion was completed by an additional restraining condition, namely, an obligatory energy release in D4 above the lowest registration threshold.

For all chosen energy ranges of electrons and protons (see table), statistical distributions of energy release dE in detectors of the instrument were obtained. The statistics of energy release distribution in detectors of the instrument a priori are unknown. In such cases, one often uses box-and-whisker diagrams (boxplot) [11]. An example of the obtained energy release distribution for electrons with energies within the range from 1 to 2 MeV is shown in Fig. 4. The points *1* in Fig. 4 designate the particles having passed through the collimator, whereas the points *2* designate the particles having passed through the instrument body. To the right of each graph, the boxplot diagrams show statistical parameters of the distributions. In this way of description of the data distribution, the height of the box in the diagram is proportional to the interval between the first and the third quartile of distribution. The median of the distribution lies inside the box, and the minimum and maximum (the values that are more

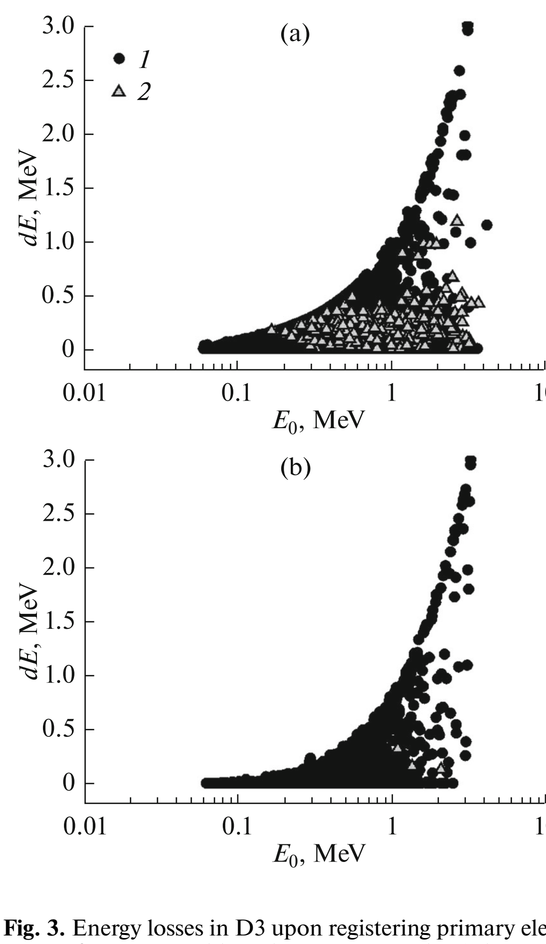

Fig. 3. Energy losses in D3 upon registering primary electrons of energy E_0 (a) without using strobe-1 (nonzero energy release in D2) and (b) with strobe-1. The events from the particles having passed (*1*) through the collimator and (*2*) through the instrument body are separated.

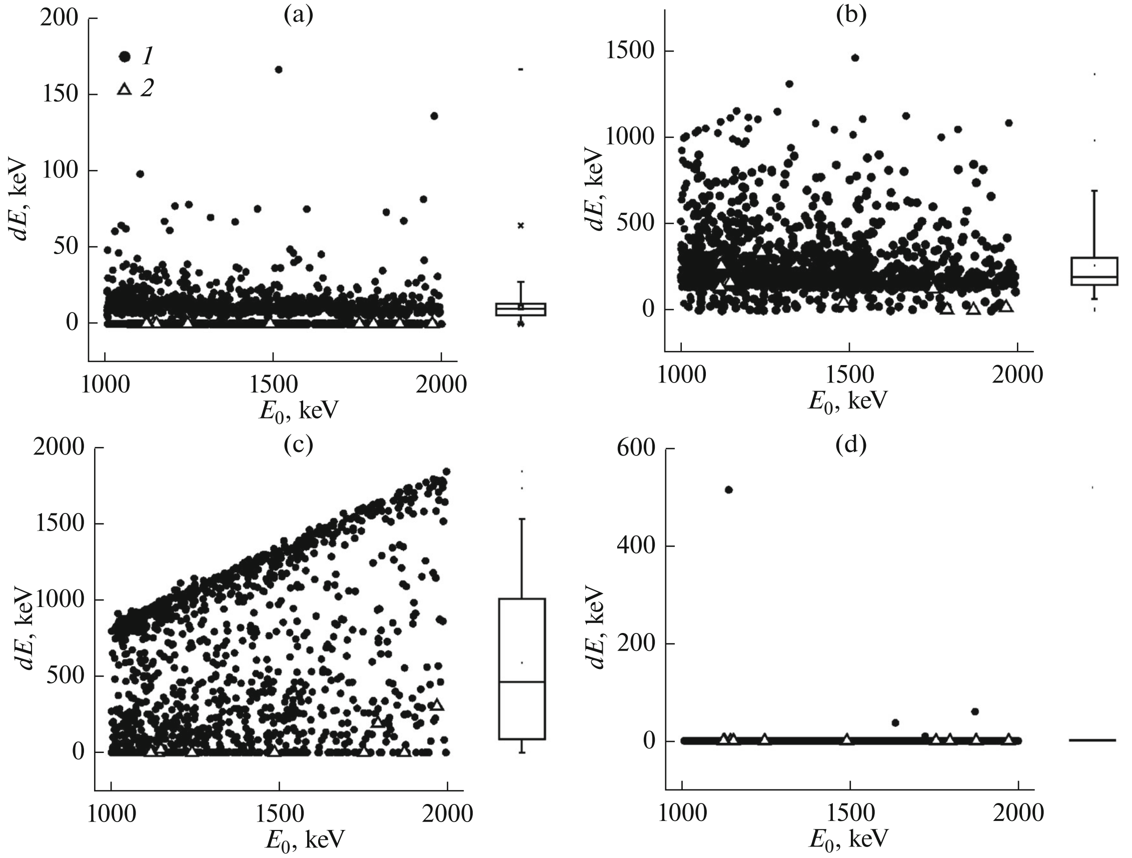

Fig. 4. Statistical distributions of energy releases in detectors (a) 1, (b) 2, (c) 3, and (d) 4 for the energies of primary electrons from 1 to 2 MeV. Here, *1* refers to the collimator, and *2* refers to the instrument body.

and less than 1.5 times the interquartile range, respectively) are depicted in the shape of segments lying above and below the box. The points situated beyond these segments are considered as the outliers of distribution and are not taken into account in the further statistical analysis of the data.

One can see from Fig. 4 that, at energies of primary electrons from 1 to 2 MeV, the signals in detector D4 are absent; detector D3 (scintillator) registers a considerable fraction of the particles; in the detector D1, all the particles lose energy not exceeding the lowest threshold of registration.

An example of statistical distributions of energy release in detectors of the instrument for the energy range of primary protons from 53 to 100 MeV is shown in Fig. 5.

It can be seen from Figs. 4 and 5 that the values of energy release in detectors have considerable fluctuations. The analysis of results of mathematical simulation made it possible to correct the limits of thresholds preliminarily chosen for each detector under the condition of a normal incidence of detected particles.

The criteria allowing one to determine energies of primary particles were established by using the obtained distributions. These criteria represent an ensemble of ranges of energy releases of primary particles with a given initial energy in single detectors of the instrument. The energy release ranges were selected by means of descriptive statistics methods [12]. However, it is impossible to get non-overlapping ranges of energy release only on the basis of statistical data, especially for electrons, since the values of energy release of particles from different energy channels can coincide. Direct application of statistical data inevitably results in errors in determination of primary energies of particles and thus in the overlapping of the channels and consequently in the distortion of registered energy spectra.

Therefore, it was necessary to calculate narrower limits of energy release containing a part of the total number of particles having passed through the collimator (for example, 50 or 90%). The lower limit of energy release in the first case is the 25th percentile and the upper limit is the 75th percentile, while in the second case, the lower and the upper limits are the 5th percentile and the 95th percentile, respectively. Therefore, for each energy channel, one can formulate its distinctive characteristics. With the chosen criteria, the logical threshold connections were determined on

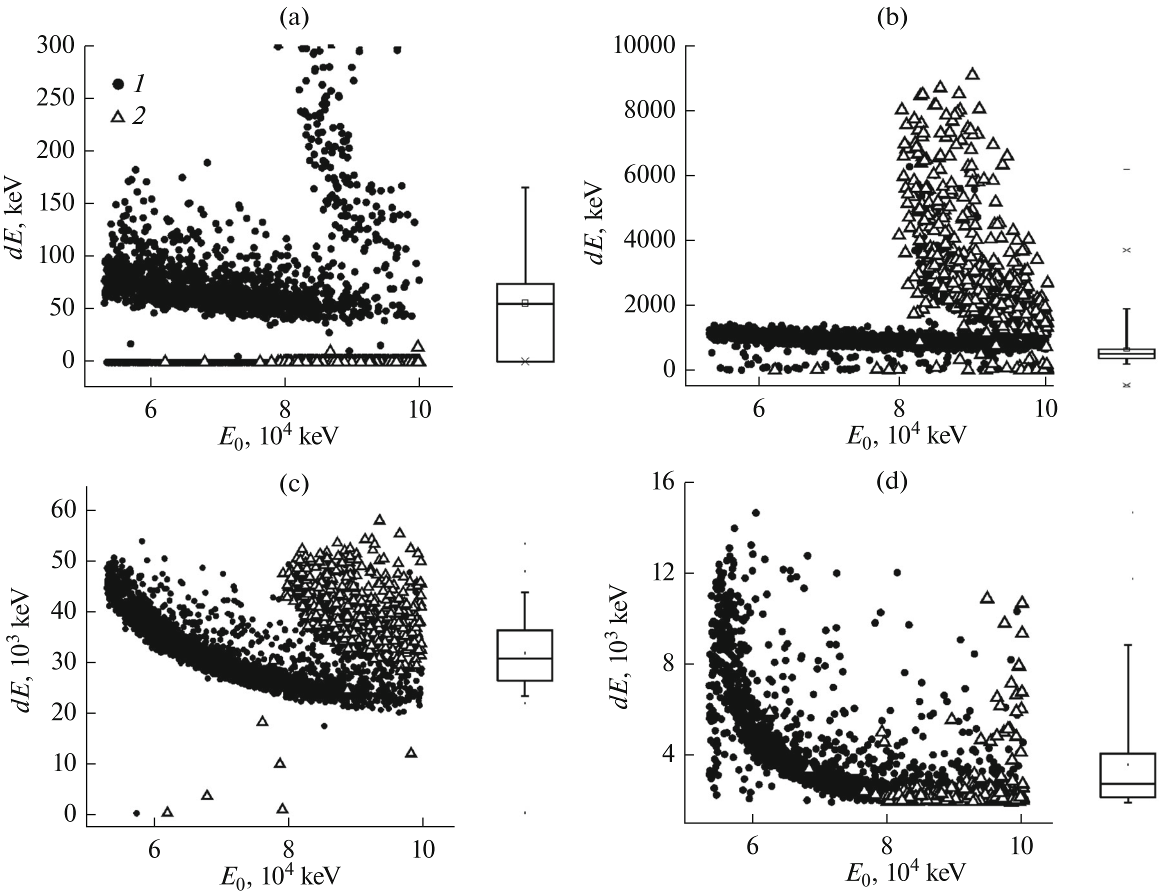

Fig. 5. Statistical distributions of energy releases in detectors (a) 1, (b) 2, (c) 3, and (d) 4 for protons with energies from 53 to 100 MeV.

the basis of principle of coincidences and anticoincidences of pulses in detectors in order to select energy ranges of electrons and protons, i.e., to determine the type of particles and their energy.

The interpretation of information obtained in such an instrument about the values of the particle flux and their energy spectra is carried out on the basis of the particle detection efficiency defined as the ratio of the number of particles registered by an instrument to the number of the particles having passed through it with a given geometry factor and specified limits of energy ranges of particle registration.

The registration efficiency for proton channels P1–P4 calculated with criteria 5–95% is 0.7–0.75. For proton channels P5–P8, one can obtain acceptable values of registration efficiency when applying stricter criteria, namely, 25–75%. In this case, the registration efficiency is about 0.4. For the electron channels, the application of the criteria 25–75% gives a registration efficiency which does not exceed 0.2. In addition, a reliable determination of the energy of electrons is possible only in the case where electrons release virtually all their energy inside the detectors of the instrument.

Comparing the selection criteria of proton parameters with the selection criteria of electron parameters obtained in calculations, one can come to the conclusion that it is possible to reduce the total number of considered energy thresholds by means of using one averaged value for several thresholds that are close to each other. Such an operation would have an insignificant effect on the accuracy of identification of the energies of primary particles, yet it would allow one to considerably simplify the logical scheme of the instrument.

Let us demonstrate an example of the reconstruction of the primary fluxes of protons and their energy spectra with use of the chosen criteria. The calculation was performed for the initial model spectrum of protons corresponding to the maximum fluxes of the inner ERB at the L-shell with $L = 1.7$ according to the model AP8. With the help of logical selection schemes, the registered events were divided into the energy ranges P1–P8 (see table) for which the values of particle fluxes passing through the collimator were calculated. An analogous procedure of division into the same energy ranges was applied to the initial spectrum. The result of comparison of these two cases is

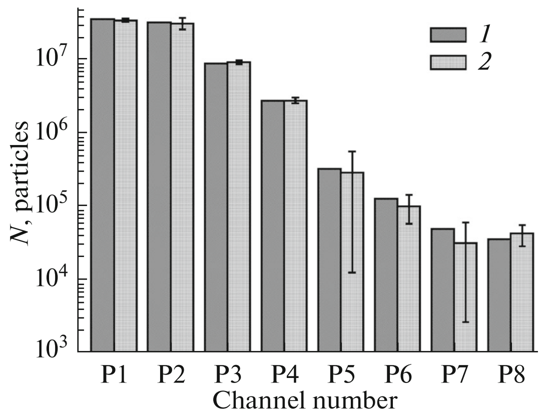

Fig. 6. Reconstruction of the initial proton spectrum at the L-shell with $L = 1.7$ with selection criteria obtained from the data at the orbit with $L = 1.4$. Here, *1* refers to the initial values of incident particle fluxes in the channels P1–P8; *2* refers to the reconstructed values with error bars obtained by using the data from detectors.

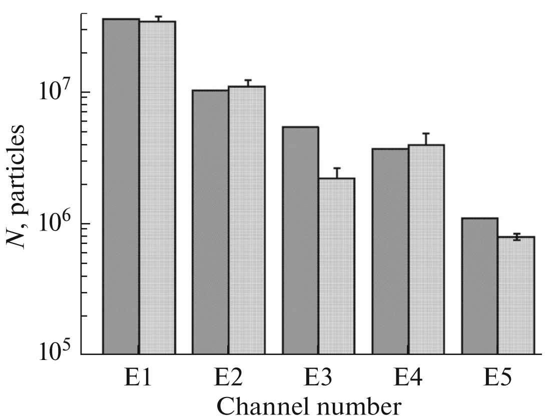

Fig. 7. Reconstruction of the initial electron spectrum at the orbit with $L = 3.2$ with selection criteria obtained from the data at the orbit with $L = 1.4$. Designations are similar to Fig. 6.

shown in Fig. 6. As follows from Fig. 6, the proton energy spectrum reconstructed by using the method of numerical simulation of the interaction of charged particles with detectors corresponds to the initial spectrum of the incident particles with quite a satisfactory exactness. A similar algorithm of reconstruction of the primary electron spectrum was applied to the maximum fluxes in the outer belt at the L-shell with $L = 3.2$. The result is shown in Fig. 7. The accuracy of determination of electron fluxes is lower than the one of proton fluxes because of much greater statistical fluctuations of the specific energy losses of electrons.

Under real conditions of a space experiment, particles of different types make simultaneous impacts on the spectrometer. Thus, there is a risk for electrons to be registered in the proton channels and vice versa. To simulate such a situation, the proton channels with their logical selection systems were exposed to electron beams with fluxes and spectra like those in the ERB. The calculations showed the complete absence of detected electrons. The same conclusion was made after having investigated the possibility of registering protons in electron channels. Therefore, it is possible to state a reliable separation of registered proton and electron fluxes.

CONCLUSIONS

The method of numerical simulation with the help of the GEANT4 software package can be used effectively for investigations of a telescopic system constructed on the basis of detectors of different types and making it possible to register separately the fluxes of protons and electrons in quite narrow energy release ranges.

The results of numerical simulation of the processes of electron and proton registration by the detection system show the possibility to exclude from analysis the signals of the particles passing through detectors out of the collimator.

Statistical methods of numerical simulation data processing allow one to refine the values of the instrument thresholds and to find the registration efficiency in single energy channels.

The considered numerical simulation method is recommended for space experiment data processing with the aim to reconstruct the initial energy spectra of protons and electrons of the ERB on the basis of the data obtained.

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