The continuous detection of gamma (X-ray) spectra registered during atmospheric precipitations

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Abstract. Monitoring of a gamma radiation in a ground atmosphere layer has revealed systematic increases during precipitations (rains, snowfalls). We have designed the instrument for the continuous detecting of differential spectra of a gamma radiation on the basis of spectrometers with sizes of scintillation crystals (Ø62×20 mm) and (Ø150×100 mm). Registration of spectra of a gamma radiation is made with high resolution by means of the 4096-channel pulse-height analyzer over the energy range from 200 keV up to 4 MeV. Responses of crystals (effectiveness of detecting) to entering radiation have been calculated with the help of GEANT4 package. Instruments posed on the continuous registration of differential spectra of a gamma-ray background. In the present paper the preliminary results of observations carried out by the new instrument are presented. Measuring of spectra during increases of the gamma (X-rays) happening during precipitations, has shown absence in the spectra the characteristic lines of any radio nuclides in all the effective range. Spectra of X-ray radiation over the range 20-400 keV, obtained earlier on the basis of crystal Ø63×20 mm, are well compounded with the data obtained with the crystal Ø150×100 mm and simulations by GEANT4 package. Joining of two detectors gives a possibility to study spectra of a gamma (X-ray) background and their variations from 20 keV up to 4 MeV.

1. Introduction

The existence of excess radiations associated with thunderstorms is a known fact [1-3]. It was shown that the main cause of the excess radiation during thunderstorms is the particles accelerated by strong electric fields within thunderclouds [1, 2].

Another very interesting phenomenon, related with generation of energetic particles by thunderstorm clouds, is “Terrestrial gamma-flashes” or TGF events. Short bursts of energetic gamma-ray quanta are observed above thunderstorm clouds during discharges between a cloud and an ionosphere. TGF events are interesting to us in connection with the developed theory of acceleration of charged particles in a discharge [4] at the presence of so-called runaway electrons [5]. However, energetic photons studied in the given work are born not in a thunderstorm, but in "quiet" rain clouds.

We organized monitoring of low-energy gamma (X-ray) radiations on the ground level and recorded increases, usually associated with precipitations. It should be noted that in the subarctic (Apatity, Murmansk region) and arctic (Barentsburg, Spitsbergen) areas, where observations were made, thunderstorms are observed extremely seldom. Nevertheless, as the cause of the increases associated with precipitations, we assume the electric field of the clouds (though not as strong as in
thunderstorm clouds), which accelerates electrons and creates the bremsstrahlung radiation penetrating to the ground level.

2. Instrumentation

We have designed the instrument for the continuous detecting of differential spectra of a gamma radiation on the basis of spectrometers with sizes of scintillation crystals (Ø62×20 mm) and (Ø150×100 mm). The main elements of the simplest single-crystal scintillation spectrometer are: a scintillator, a photomultiplier tube, a spectrometric amplifier and discriminators. Registration of spectra of gamma radiation carries out with high resolution by using the 4096-channel pulse-height analyzer over the energy range from 20 keV up to 4 MeV.

The new detector was incorporated in the complex performing continuous measurements of radiation in the ground layer. Thus, continuous monitoring of X-rays is performed in the energy range from 20 keV to 4 MeV. In the subrange 20 – 300 keV using a small scintillation detector based on the crystal NaI(Tl) the size of Ø63 × 20 mm [6, 7], and in the range 300 keV – 4 MeV using a new large scintillation detector.

Register gamma-ray spectra is performed by two different channels. In the first channel pulses with amplitude proportional to the absorbed photon energy, transmitted to the amplitude discriminators. Those discriminators form channels 20, 100, 200 and 1000 keV, the data of which are transmitted to a computer-collector. The second channel is differential. The pulses from the large detector transmitted to the 4096-channel pulse analyzer. Data from the analyzer are recorded by a special computer. Therefore the measurements of the differential spectrum of gamma radiation in the range 200 keV – 4 MeV are carried out. Accumulation time of one spectrum is set for 30 minutes. The greater accumulation time provides accuracy of the spectrum. However, the maximum time of collection imposes a limitation by the duration of the observed increases. The shortest of the observed events have duration of not less than two hours.

X-ray emission spectra in the range 20 – 300 keV, obtained earlier by a small detector, in good agreement with the new spectrometer, both in form and in absolute value.

In the given work, using advanced simulation tools, we calculated the detection efficiency of spectrometers with application of several modeling concepts to obtain more accurate results. The obtained simulation results are in very good agreement with experimental data.

3. Modeling

To calculate the different geometry spectrometers, we used our model written with the help of Geant4 toolkit.

For the same reason, the geometry of the model has been simplified and presented as a simple cylinder of appropriate size (placing aluminum reflector is meaningless, since the optical photons are not involved in the simulation). In front of crystal was placed a simulation particle source with the discrete values of energy (10 keV, 20 keV, 30 keV ... 400 keV).

To calculate the efficiency of the crystal with the geometrical dimensions of 10x15 cm using a different concept, because this scintillator detects the gamma rays in a wide energy range, where may appear such processes as the formation of an electron-positron pair. Therefore, if we use the method described above, the detection efficiency will be greatly increased with increasing energy of an initial gamma-quantum. For this model, we took into account the processes of scintillations, which are defined by the description of the processes G4PhysicsList and scintillation properties of the material in class G4DetectorConstruction in accordance with the data taken from the reference book [8].

The geometry of the spectrometer used in the simulation is shown in figure 1. Because photons are involved in modeling, then the boundary separating the media (aluminum-crystal) are defined with reflecting properties using a glisur model of G4OpticalSurface class (glisur model taking into account the polished surfaces provide the specular reflection). With the help of our class G4SensetiveDetector detector was implemented in two ways:
- Energy Binned Scorer – for collect a histogram of detected gamma rays and then comparing these results with experimental data
- Particle Scorer – a simple counter of the optical photons reached the window of the photomultiplier, is necessary for direct calculation of the efficiency of the crystal

Accordingly, the detection efficiency of the crystal with the geometrical dimensions of 10x15 cm is defined by a simple formula:

\[
\varepsilon(E_{\text{prim}}) = \left( \frac{N_{\text{photons}}}{L_{\text{scint}}} \right) \frac{E_{\text{scint}}}{E_{\text{prim}}}
\]

(1),

where \( N_{\text{photons}} \) is the number of photons is reached the window of photomultiplier, \( L_{\text{scint}} \) is scintillation yield, which determines a number of optical photons formed during a scintillation per unit of energy of an initial gamma-quantum, \( E_{\text{prim}} \) is energy of initial gamma-quantum, \( E_{\text{scint}} \) is energy spent to the scintillation process only.

As seen from above, we take into account energy spent only in the process of scintillation, and thus we obtain correct way to determine the effectiveness of the crystal.

For comparison the modeling data with the experimental measurements, the modeling of the radiation sources with to lines 27 keV and 60 keV, which corresponds to the emission lines of \(^{241}\)Am has been used. It also the source with the line 662 keV, which corresponds to the line emission of gamma-rays \(^{137}\)Cs, has been used.

4. Results and Discussion
As a result of simulation in the given work the detection efficiency of crystals NaI(Tl) with the geometric dimensions 2x6.3 cm (figure 2a) and 10x15 cm (figure 2b), as well as the spectrum of detected gamma-ray source in case of \(^{241}\)Am for small detector (figure 3a) and \(^{137}\)Cs for large detector (figure 3b) has been obtained.

From the graph of comparing the spectra of gamma rays quanta is seen that the model results and experimental data for small detector (figure 3a) are in very good agreement. Some discrepancies in the 27 keV line can be caused by noise in the amplifier of the real spectrometer. For the large detector (figure 3b) the model results and experimental data are in not so good agreement. This can be explained by the degradation of the crystal detector used in the experiment. For the new detector energy resolution should be about 10-12%. But for our detector energy resolution is about 20%.

From the above it follows that the model can be used for precise calibration of the spectrometers of similar type, and (taking into account the changes in parameters of the materials) for other types of spectrometers, such as CsI(Tl), etc.
Figure 2. Modeling X-ray detection efficiency for a small detector (a) and large detector (b).

Figure 3. Comparison of experimental data (red line) and model data (blue dots) for radiation source in case of $^{241}$Am for small detector (a) and $^{137}$Cs for large detector (b).

5. References

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