**N E W S**
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
**SERIES OF GEOLOGY AND TECHNICAL SCIENCES**
ISSN 2224-5278
Volume 1, Number 433 (2019), 38 – 50 **https://doi.org/10.32014/2019.2518-170X.4**

UDC 551.521.64

**A. L. Shepetov[1], T. Kh. Sadykov[2], K. M. Mukashev[3], L. I. Vildanova[4], A. D. Muradov[3], O. A. Novolodskaya[2], M. E. Alieva[5]**

[1]P. N. Lebedev Physical Institute of the Russian Academy of Sciences (FIAN), Moscow, Russia,
[2]Institute for Physics and Technology, Almaty, Kazakhstan,
[3]Al-FarabiKazakh national university, Almaty, Kazakhstan,
[4]Tien Shan Mountain Cosmic Ray Station of FIAN, Almaty, Kazakhstan,
[5]Abai Kazakh national pedagogical university, Almaty, Kazakhstan.
E-mail: ashep@www.tien-shan.org, turlan43@mail.ru, mukashev.kms@gmail.com, luvild@mail.ru, abyl.muradov@gmail.com, novololga@yandex.ru, moldir-2008@mail.ru

# THE GEANT4 SIMULATION OF AN ELECTRON-PHOTON AVALANCHE DEVELOPMENT IN THUNDERCLOUD ATMOSPHERE

**Abstract.** On the basis of Geant4 toolkit we created a special program for simulation of the electron-photon avalanche development in a large-size atmospheric electrical fieldunder typical environmental conditions of the Tien-Shan mountain cosmic ray station. This code is especially aimedat planning and analysis of experimental results obtained in the frames of thunderstorm investigation program *Groza*.

The main simulation predictions concerning the electromagnetic components of avalanche: relative abundance of the electron and gamma ray components (30:1), their energy spectra (approximately, a power law shape with differential index -1.5-2 in the range of 30-10000 keV), and the anisotropy of their angular distributions occur in a good agreement with the results of theoretical and experimental studies which have been made so far under mountain conditions. The predicted value of the gamma ray ox which is of the order of $10^2$cm2 at observation level also corres-pond reasonably well to direct measurements made at Tien - Shan station. These agreements confirm the adequacy of the used simulation model to real thunderstorm events.

At the same time, the predicted ox of avalanche neutrons seems to be an order of magnitude underestimated in comparison with data of corresponding experimental measurements; such a rough discrepancy can be an evidence of the existence of some effectivemechanism of neutron generation in natural atmospheric discharges, besides the fully electromagnetic photo-nuclear and electron-nuclear interactions which have been applied in simulation.We discuss the requirements to design of experimental $set-ups$ appropriate for study of thunderstorm connected radiations at mountain height which follow from presented simulation.

**Keywords:** thunderstorm, lightning, atmospheric electricity, runaway breakdown, Geant4.

**Introduction.** An investigation of the processes of atmospheric electric discharge in thunderclouds (lightnings), and of the role of cosmic rays in discharge initiation is held at the Tien Shan mountain cosmic ray station during two last decades. The complex experimental installation *Groza* (i.e. "Thunderstorm") which has been created especially for this purpose gives a possibility of simultaneous registration of various types of energetic radiations generated at the time of discharge: the X-ray and gamma radiation [1 - 3], accelerated electrons [4, 5], the 0.1-30 MHz and 250 MHz radio emission [6-8]. A separate task is registration of the extensive air showers being born in thunderstorm atmosphere by energetic cosmic ray particles, and the study of their role in the initiation of lightning discharge [5, 9, 10]. Another open question which remains so far unclear is connected with multiple observations of neutron signal probably associated with lightning discharge, which have been made both at Tien Shan [11, 12], and reported in publications of other groups [13-18].

Specificfeature of the *Groza* experimental complex is its mountain location just at the height of thunderclouds, so at thunderstorm times its detectors frequently occur being immersed immediately inside the lower part of active zone of the cloud where intensive electric field is present, and acceleration of charged particles have its place. Hence, for analysis of the data gained in this experiment, it is convenient to use the theoretical information concerning expected behavior of the charged particles ow within the range of a large scale atmospheric electric field. Such information could be obtained by the means of Monte-Carlo simulation of discharge development in a media which corresponds to characteristic conditions of Tien Shan experiment: the height of detector disposition between 3-4 km above the sea level, the spatial size of electric field region of the order of some kilometers, a rather low energy threshold of the used particle detectors (the thresholds about 30-50 keV for gamma-radiation, 1-3 MeV for electrons, and of the order of thermal energy for the neutrons aretypical for *Groza* experiment). Also, it is desirable to use a possibly complete set of existing particle models with precise account for interaction physics in a wide range of particle energies: from some hundreds of eV for secondary avalanche electrons, and up to some GeV for initial cosmic ray particles. These demands are met successfully by the modern program toolkit *Geant*4 [19] which is commonly used for simulation of particle interaction by analysis of the results of high energy physics and cosmic ray experiments in the leading centers of modern particle research:CERN, FERMILAB, IceCube, Auger installation etc.

The subject of present paper is the development of a proper *Geant*4 model for simulation of the particle avalanche behavior in thundercloud atmosphere, and the testing of its predictions in comparison with known theoretical and experimental data on thunderstorm generated particles axes. Later on, the simulations of this kind are intended for using in quantitative analysis of experimental data and in planning of appropriate detector design, in particular for the Tien Shan complex installation Groza, and can be useful in realization of other similar experiments.

**Simulation model.** Especially for the analysis of the data of Groza experiment, a simulation model was built on the basis of Geant4 toolkit which takes into account typical characteristics of as it is shown in figure 1, the spatial region to trace the particle trajectories in is a 5x5x5 $km^3$ cube, and its geometrical center is accepted as an origin of the general coordinate system, with Z axis being directed "vertically" to the top side of considered volume. The whole space is supposed to be filled by the air with standard gas composition (75.5 mass percent of N, 23.2% O, 1.28% Arand 0.01% C). The air pressure and temperature at "bottom" side of model volume are set to 675 mbar and 10°C correspondingly, in agreement with average atmospheric conditions at the altitude of Tien Shan station, and with elevation h above this level both the pressure and air density diminish exponentially (~exp(-h/$H_0$)) with characteristic scale height $H_0$ = 8,4 km. The temperature decrease with altitude is accepted to be linear with the rate of $6^0$C/km. of the local Tien Shan environment.

According to common views, the key role in generationof electric eld in thunderclouds must play the convection mechanism of charge separation driven by the *E*arth'sgravitation [20], which generally acts in vertical direction.Correspondingly, in considered model it is set a uniformelectricfield *E* within a 1.5 $km^3$ km high vertical cylinder with its direction parallel to axis, to ensure downward acceleration of the negatively charged particles (electrons). This supposition agrees with modern data on existence of the lower positively charged region in thundercloud structure [21]. The geometric center of cylindrical field region coincides with the center of enclosing cube.Hence, the bottom side of the model cubic space corresponds to observation level of *Groza* experiment, and1 km above it occurs the lower border of the electricfieldregion, like a situation commonly met in real thunderstorm events. The value of the field strength $\varepsilon$ was kept constantin each simulation run, and have been varied between 0.5-2.0 kV/m in different calculation series (more on this seebelow in section 3).

As one of the reasons which could trigger an electricdischarge within thundercloud it is often considered thepresence of charged seed particles in atmosphere, in particular electrons of extensive air showers (EAS) which areborn abundantly by the $10^{14}$-$10^{16}$ eV primary cosmic raysnuclei [22, 23]. Following to this mechanism, in each simulation series the seed electrons with fixed energy wereplaced just in the center point of considered model volume, and the directions of their initial momentum wererandomly spread inside the $4\pi$ solid angle (since the real EAS particles can y into thundercloud internals from anyside).A number of simulations was made with primary energy varied in the limits of 100-1000 MeV since these are the energies which are typical for the most part of EASelectrons. The

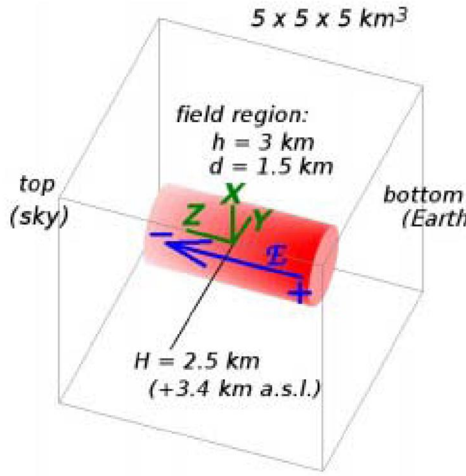


Figure 1 –Geometry of the Geant4 simulation model.
It is supposed that the "bottom" side of model volume sits at the altitude of Tien Shan mountain station
(3.4 km above the sea level)

subsequent history of the seed particles soas of all succeeding avalanche products was traced in every simulation run: the energy, momentum direction, 3D-coordinates of the start and final track point, and arrivaltime to the end of trajectory (counted since the momentof primary interaction) were kept for each product particlefor further analysis.

The set of *Geant*4 physical models included insimulation involves the common processes of electro-magnetic physics: the bremsstrahlung, multiplescattering, and ionization losses for electrons; thephoto-, and Compton-effects, and pair productionfor gamma-radiation; and the positron annihilation (correspon-dingly, the modules *G4eBremsstrahlung*, *G4eMultipleScattering*, *G4eIonisation*, *G4PhotoElectricEffec*t, *G4ComptonScattering*, *G4GammaConversion*, *G4eplusAnnihilation* of theGeant4 toolkit [24, 25]). Electromagnetic interactions ofany charged hadrons were taken into account throughcorresponding model processes *G4hMultipleScattering* and*G4hIonisation*.

Since the presence of low-energy charged particles whichcould be accelerated by the fieldis essential for the taskwe are interested in, the trajectories of both electrons andgamma-quanta were traced until their kinetic energy fallsdown a rather low threshold of 100 eV (due to ionizationlosses and photoelectric effect correspondingly). At thesame time, in the output set of resulting simulation datafor further analysis (e.g. to make a deposit into distributions presented below) were included only the particleswhich had the energy above 30 keV in point of theirtrajectory, in accordance with lower registration limit ofsome tens of keV which is typical for *Groza* detector complex.

The possibility of neutron production inside the developing electron-photon avalanche was ensured by the means of photo- and electronuclear reaction models from the standard Geant4 distribution (*G4GammaNuclearReaction, G4ElectroNuclearReaction*). Specific feature of neutron secondaries is chaotic trajectories resulting from a series of elastic collisions with nuclei of surrounding matter. Since we are interested in distribution of various characteristics of avalanche productsat a number of fixed distances from the active zone of thundercloud, every neutron born in simulated avalanche was traced completely along its trajectory through all intermediate elastic interactions, and in the final dataset wereincluded only its characteristics (the energy, momentumdirection, etc) which happened to be in the most distant points from the center of model ”thundercloud” volume (but which can occur being not a final point of the wholetrack). The simulation module for neutron physics takesinto account the Geant4 models of elastic coincidences inthe range from thermal and intermediate energies (~$10^{-2}$–4 eV, G4NeutronHPThermal Scattering) to the high neutron energies (4 eV–20 MeV, *G4Neutron HPElastic*), andfurther on up to some GeV (*G4LElastic*). Correspondingly, the inelastic neutron interactions are presented bythe low- (~$10^{-2}$eV–20MeV, G4NeutronHPInelastic) andhigh-energy (20 MeV–5 GeV, G4BinaryCascade) reaction models. Besides, the low- and high-energy neutron capture models (*G4NeutronHPCapture and G4LCapture*) aretaken into account.

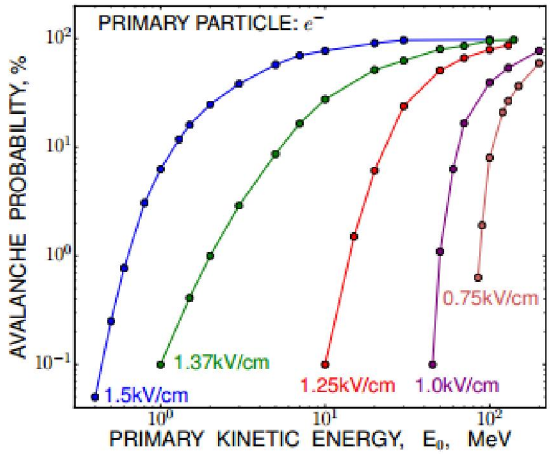


Figure 2 – The probability of an electron-photon avalanche generation in dependence on initial energy of the seed particle $E_0$ and the strength of electric field E (varied from 0.75 up to 1.5 kV/cm)

The necessity to consider rather high energy of theorder of some GeV in present simulation is stipulated bythe need to take into account the product particles of thehigh energy cosmic ray interactions.

For protons, anti-protons, and charged pionstogetherwith analogous processes of elastic and inelastic hadronicinteractions the models of multiple scattering and ionization losses are considered (for negative pions-alsothe process of their nuclear capture at rest, and for antiprotons, the annihilation process). Interaction sets ofall unstable particles include the process of their decay(*G4Decay*).

**Simulation results.** *Generation probability of a discharge avalanche.* The conditions of effective avalanche generation in thunderstorm atmosphere are the subject of a number of theoretical papers concerning the theory of runaway breakdown mechanism [26-28] which is connected with energetic electrons from the tail of thermal energy distribution and seems now to be one of the leading probable hypothesis on the development of electric discharge in thunderclouds.The main conclusions which follow from this theory are the following: (1) the development of an electron-photon avalanche is possible in the field ε with the strength above some critical value $\varepsilon_c$, which is about 2.0−2.2 kV/cm at the sea level, and for the heights of the Tien Shan detector complex $\varepsilon_c \approx 1.3{-}1.4$ kV/cm; (2) some charged seed particles must be presented within the filed region, e.g. the fast electrons from cosmic ray interaction with typical energy $E > m_e c^2 \varepsilon_c / 2\varepsilon$ (which corresponds to condition of $E \geq 200 - 500$ keV for a near-critical field); (3) the characteristic spatial size of the field region must exceed the typical length of exponential avalanche development (about 100 m). The geometry of considered simulation model does satisfy all these demands.

In present simulation, the probability of an electron-photon avalanche was defined as a relation of the events with multiple generations of secondary product particlesto the total number of simulated events. As a sign ofavalanche development the threshold condition $N_{sum} > 10000$ was applied, where $N_{sum}$ is the sum number of secondary particles with the energy above 100 eV born in successive interactions of primary electron; as preliminarysimulations have shown, in the absence of field this condition gives a correct (zero) probability of avalanche generation excluding from the count δ-electrons and the particlesof usual low-energy electron-photon cascades.The resulting distributions of the avalanche generationprobabilityare presented in figure 2 in dependenceonthe strength of electric field ε and the energy of primaryparticle$\varepsilon_0$. It is seen that the probability of avalanche appearance depends strongly both on the energy of the seed particle and on the tension of electric fieldε.

This probability starts to be noticeable (>10% of the total number ofsimulated events) by the strength of model field E ~1.2-1.5 kV/cm, just about the value of critical field $\varepsilon_c$atwhich the discharge development do occur at the altitude of Tien-Shan station due to the runaway breakdown mechanism (according to [28], $\varepsilon_c \sim 1.0$ kV/cm for the height position of the model "cloud" center, $\varepsilon_c \sim 1.2$ kV/cm atits lower border, and $\varepsilon_c \sim 1.4$ kV/cm at the altitude ofTien Shan station). On the other hand, the test simulation runs have shown that any attempts to increase the model field above 1.5 kV/cm lead to exponential growth of the multiplicity of secondary products even with the seed particle energy $\varepsilon_0$ below 1 MeV, which means an excess of the $\varepsilon_c$ threshold and transition into overcritical regime. Such an almost quantitative coincidence can confirm the principal correctness of the used simulation model.

Since it is well known that in real thunderstorm clouds the field values $\varepsilon>\varepsilon_c$ were never observed [29, 30] all simulation results presented below were obtained in the runs with a fixed tension of the model electric field$\varepsilon$ = 1.5 keV/cm.

*Electromagnetic components of avalanche.*The spatial and energy particle distributions in discharge avalanche was studied through building the energy spectra of generated secondary particles at different distances ***d*** from the center of the field region. Since in accepted simulation model this center coincides with the origin of coordinate system, the distance was defined as $d=\sqrt{X^2+Y^2+Z^2}$, where the coordinates (x, y, z) correspond to the end of simulated particle track.The resulting energy spectra for electron and gammaray avalanche components are presented in two plots on the top of figure 3. The spectra are shown separately for various ranges of distance *d* which correspond both to inside of the spatial region of electric field: *d* = 0.75-1 km (curves 1), *d* = 1.25-1.5 km (2), *d*=1.5-1.75 km (3); and the space outof the field: d=2.0-2.25 km (4) *d* =2.5-2.75 km (5), *d*=2.75-3 km (6), *d*=3.25-3.5 km (7).

A characteristic feature of figure 3 spectra is the fast decrease of their intensity at the boundary of electric field: just at the 2 km distance from center point theparticle intensity is an order of magnitude below its average value within the field region, and at the distance~2.5 km (which corresponds to observation level in considered simulation model) it is up to 100-300 times lowerthan in the field center. Hence, a practical conclusion canbe drawn that for effective registration of the high-energyelectromagnetic components of a discharge avalanche it isextremely desirable to place the detector system just inside the spatial region of particle acceleration i.e. at apossibly high altitude above the sea level, just within thethundercloud region.

Analogous conclusion on rapid recession of the particledensityhas been made in theoretical work [28] where the equations of kinetic theory were applied to study of therunaway breakdown effect. Also, the fast absorption ofgamma-radiation emitted by lightning discharges was immediately observed at Tien Shan installation with a set ofsynchronously operating gamma-detectors distributed in a wide range (~500 m) of altitudes over a mountain slope [2, 3].

For comparison with situation of the real thunderstormevents, the energy spectra of some transient radiationbursts which have been registered experimentally in the moments of close lightning discharge at Tien Shan areshown on the top plots of figure 3 with triangle-shapedmarkers. In these measurements, the gamma-rays wereregistered with a scintillation detector based on a cylindrical NaI crystal, 110 mm in diameter and 110 mm in the height, which has been equipped with a number ofthreshold counter schemes to select scintillation pulses indifferent amplitude ranges, while the electron spectra wereobtained with a multi-layer absorption spectrometer ona set of ionization counters.

The registration system of signal intensity in these measurements was strictly synchronized with the moment of atmospheric discharge by aradio-pulse from the lightning and operated with a 160 μstime resolution, so the pulses of transient radiation wereseen distinctly around the discharge moment, and their relative excess above the background count level can becalculated. A more detailed description of the Tien Shandetector system and the current experimental setups canbe found in [31].

In the two upper plots of figure3 it is seen a rather satisfactory agreement both in general form and slope between the simulated and experimental spectra.The expected angular and time distributions of the electron and gamma ray intensity are presented in the middle panels of figure 3. Zenith angle of particle arrival at a distinct distance d by simulation was calculated as$\theta$ = arcos(z/$d=\sqrt{X^2+Y^2+Z^2}$), where the (x, y, z) coordinates relate to the final point of particle trajectory. Since in accepted simulation geometry the electric fieldis supposed to be directed along the *Z* axis, the angle $\theta=180^{\circ}$ corresponds to acceleration direction of the negatively charged particles.

It is seen that angular distributions have an asymmetricshape which is strongly elongated in backwardhemisphere,i.e. along the acceleration direction of electrons. Such a concentration means that the scattering processes do notplay any significant role, and the most part of electron andgamma radiations keep the direction distribution formedinside the acceleration area until the distance up to somekilometres. Similar anisotropy for distribution of gamma radiation has been obtained also in [28] on the basis ofkinetic theory, and in a study of the behaviour of highenergy charged particles in a strong atmospheric electricfield made with the use of CORSIKA simulation package[32].

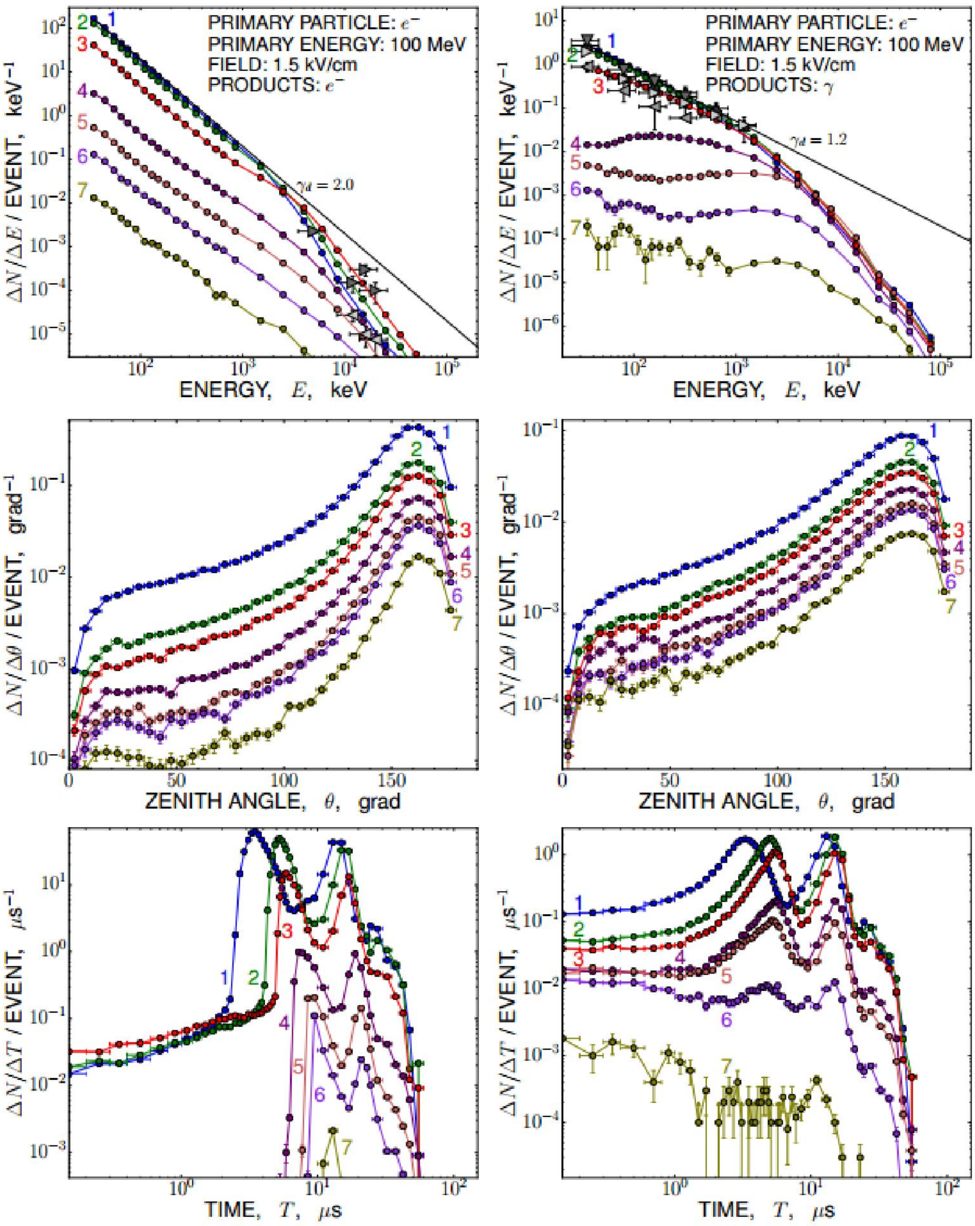


Figure 3 – The simulation results concerning electromagnetic avalanche components. Top plots: differential energy spectra of the electrons (top left) and gamma-ray quanta (top right) obtained in simulation and seen both in- (curves 1–3) and outside (curves 4–7) of electric field region (see text); with separate triangle marks are shown the spectra of real radiation bursts registered experimentally by close lightning discharges [31]. The middle and bottom plots: the angular and time distributions of the intensity of avalanche electrons (left), and gamma rays (right); the curve numbers and distance intervals in these plots are the same as for corresponding energy spectra. Error bars correspond to statistical errors of either Monte Carlo simulation or experimental data points

Two distributions in bottom plots of figure 3presentthe time delay between the beginning of avalanche development and arrival of corresponding radiation particles tothe points placed at the distance ***d*** from the center of thefield region. At observation level (d~2-3 km) both distributions have a prominent maximum in the region of 10-30 μs, in agreement with characteristic spike-like recordsof the gamma radiation signal which have been repeatedlyregistered in Tien - Shan experiments [2, 3, 8] held with a100–200 μs time resolution. This result means that the requirement of a precise timing analysis of signal intensitywith a better resolution time of the order of some microseconds is essentially desirable by design of experimental setups aimed to the investigation of thunderstorm connected radiations.

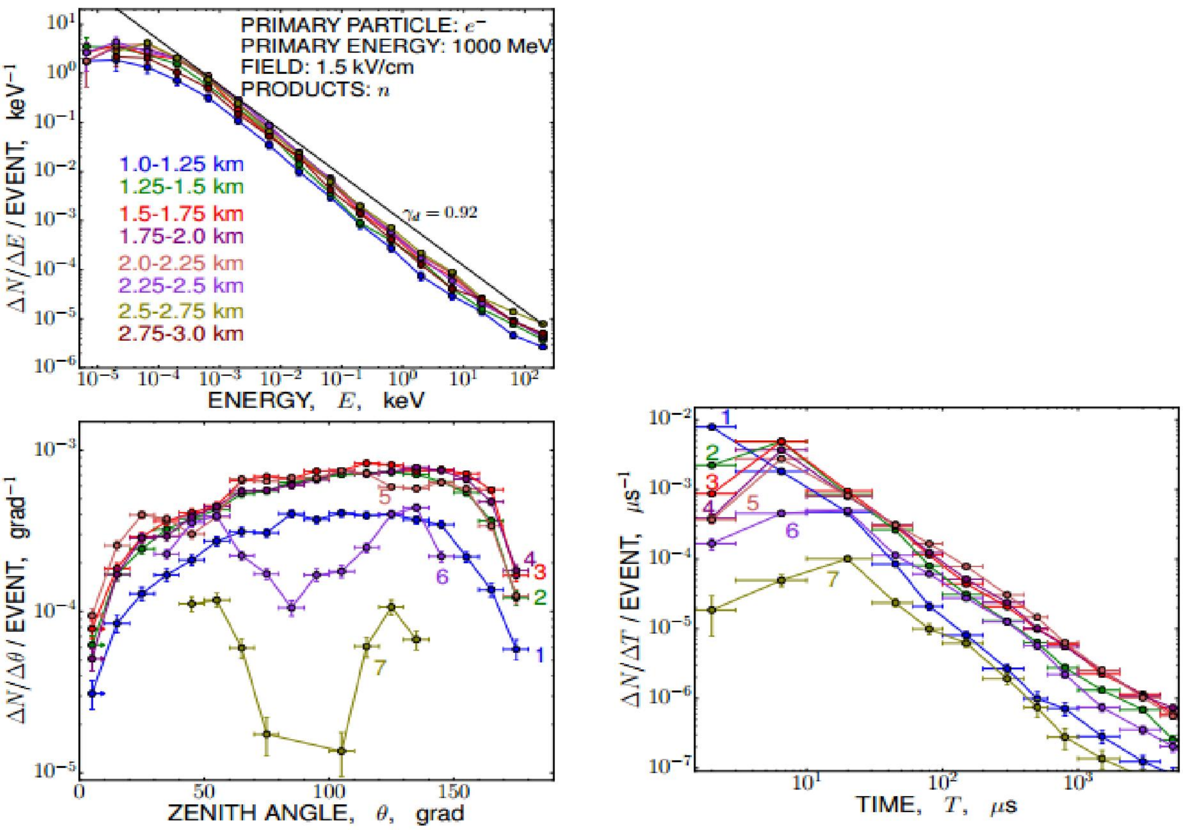


Figure 4 – The simulation results concerning the neutron component.
From top to bottom: the differential energy spectra of avalanche neutrons both within and out the region of electric field;
the angular and time distributions of the neutrons born
by avalanche curves 1 in both plots correspond to the distance range d=0.5–1.0 km from the field center,
(curves 2 to the range 1.0-1.5 km, 3 - to 1.5-2.0 km, 4 - to 2.0-2.5 km,
5 - to 2.5-3.0 km, 6 - to 3.0-3.5 km, and 7 - to 3.5-4.0 km)

Besides electrons, the trajectories of positron typeavalanche products were traced in simulation as well, andcorresponding energy spectra, zenith angle, and time distributions were obtained analogously to the case of electron particles. The shape of all these distributions is quite similar to the shape of electron ones, but relative intensityof positron component is 2.5–3 orders of magnitude lower. Fromthis one can state that the positively charged particles do not play any significant role in formation of signaldetectable in installations of *Groza* experiment.

Generally, a rather satisfactory agreement achieved between the computation, experimental, and theoretic results on the electromagnetic avalanche components can beconsidered as an ample correctness proof of presented simulation.

*The neutron component.*In the upper plot of figure 4theenergy spectra of the neutrons born by avalanche development are shown which have been calculated over thevarious distance ranges from the center of electric field. Incontrast to the case of gamma ray and electrons, the differential energy spectra of neutron component demonstratetheir practical independence on the distance; all of themhave the same power law shape with differential index $\gamma \approx$-0.92, and the close absolute intensity. Hence, a noticeab-leneutron signal could be expected at a rather significant distance, up to 2-3 km from discharge region; and the lowenergy neutrons must absolutely prevail among this signal:it is seen that the intensity of ther-mal neutrons is up to~$10^6$times above its value in the MeV energy range.The angular distribution of the neutron type products in simulated avalanche is shown on the middle plot of figure 4.This distribution is much more isotropic than in the caseofelectromagnetic component, and both within the fieldregion (curves 1,2,3) and at a rather significant distancefrom it (curves 4,5) it is practically uniform in a wide range of zenith angles.

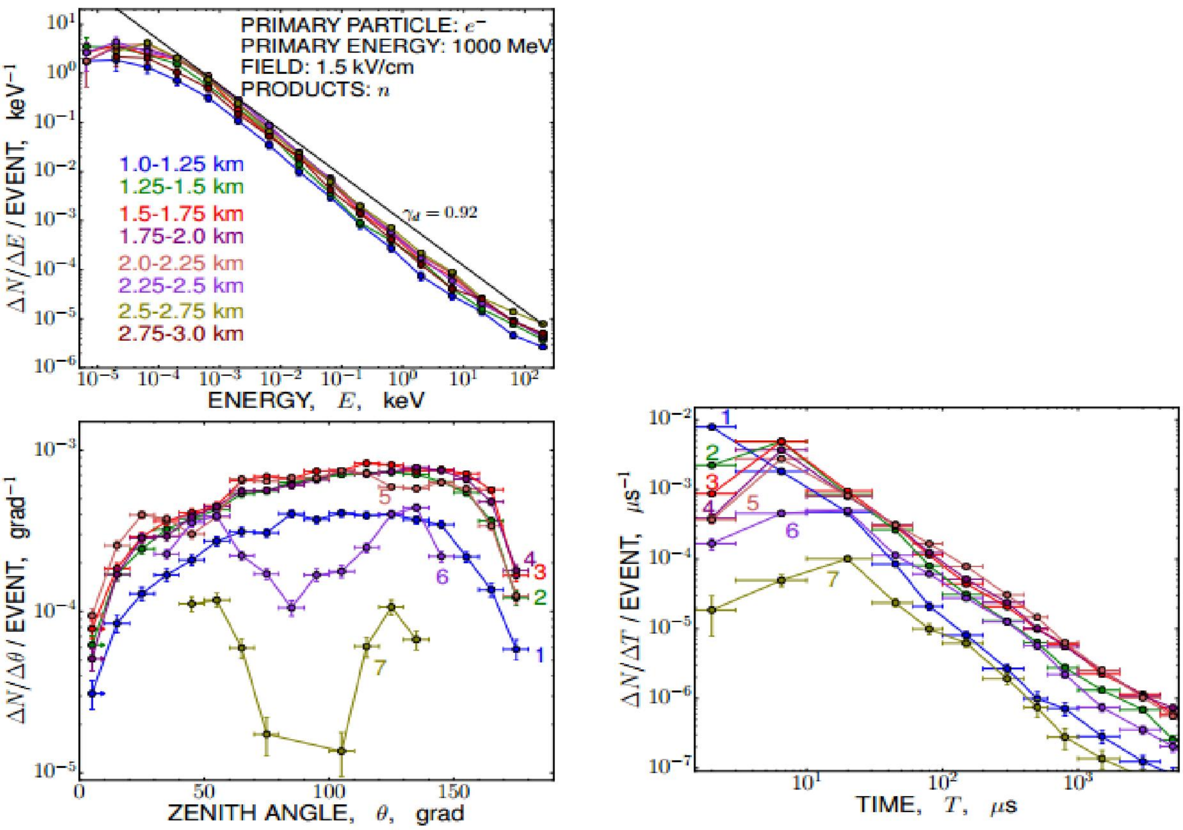


Figure 4 – The simulation results concerning the neutron component. From top to bottom: the differential energy spectra of avalanche neutrons both within and out the region of electric field; the angular and time distributions of the neutrons born by avalanche curves 1 in both plots correspond to the distance range d=0.5–1.0 km from the field center, (curves 2 to the range 1.0-1.5 km, 3 - to 1.5-2.0 km, 4 - to 2.0-2.5 km, 5 - to 2.5-3.0 km, 6 - to 3.0-3.5 km, and 7 - to 3.5-4.0 km)

The distribution of the neutron arrival times at differentobservation distances is shown in bottom plot of figure 4.It is seen that the maximum of neutron signal is achievedat typical times about 1-10 μs after initiation of discharge avalanche. Up to the times of ~30-50 μs the relative decrease of neutron intensity does not exceed an order ofmagnitude, in contrast to electrons and gamma raywhichtend to disappear completely at this time. The neutronintensity remains at noticeable level (above 1% of its initial intensity) until the times of 100-300 μs which is theconsequence of a comparatively long life time of thermal-neutrons in atmosphere. From this, a practical conclusionfollows that any detector system aimed for experimentalregistration of neutrons born in an atmospheric discharge must have a considerable collection time of neutron signals,and the duration of data sampling periods of the order ofsome milliseconds besides the microsecond scale time resolution are desirable. At present time, these requirementsare satisfied in detector design accepted in *Groza* experiment.

It should be stressed that the low time delays ≤10 μsbefore registration of neutron signal at a distance of somekilometers from discharge region predicted by simulationare direct consequence of the accepted mechanism of neutron production, where relativistic particles: the gammarays and high energy electrons play an intermediate role,and can be responsible for the fast neutron origin just invicinity to observation level. In practice, both the momentary and largely delayed (over a time of millisecond order) signals from neutron detectors have been registeredin Tien - Shan experiments [12].

*Relative composition of discharge avalanche*. The figure 5presents distribution of simulated events over the multiplicity $M$ of different types of secondary product particles generated at avalanche development. For both electromagnetic components$M$was calculated as a sum number of,correspondingly, electrons and gamma ray quanta with theenergy above 30 keV which have been found in simulate-davalanche, for the neutron component the multiplicity was counted without any energy threshold; all distributions arenormalized to a total number of generated avalanche events.

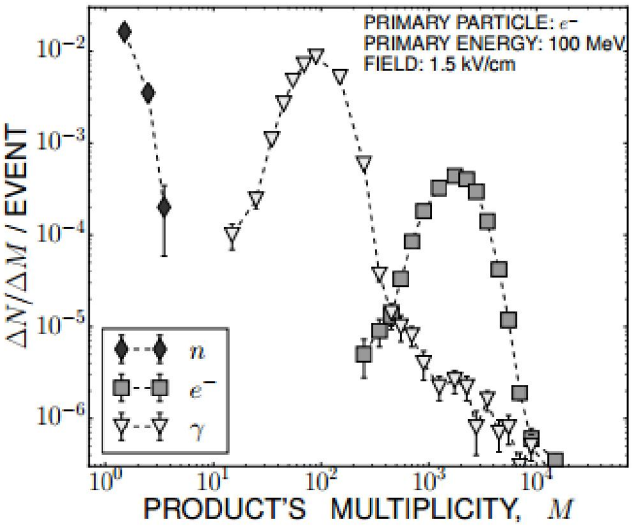


Figure 5 – Probability density functionsofmultiplicity distribution of secondary products in simulated discharge avalanche

In comparison of distribution maxima positions in figure 5 it is seen that electrons do prevail in the avalanche,while the relative intensity of gamma ray flux must be 20-30 times lower. Obviously, the significant abundance difference between electromagnetic components in an avalanche driven by electric field results from acceleration of low-energy electrons, and this is a specific feature ofthis type of atmospheric cascade which principally differs from the cascades of extensive air showers (EAS) initiatedby cosmic ray particles, where a dynamic equilibrium constantly exists between both the electron and gamma raycomponents.

According to figure 5, the multiplicity of neutron signals is quite negligible, about some particles per a simulateddischarge avalanche. Seemingly, this prediction does contradict to existing observations of thunderstorm relatedneutron signal in experiments mentioned above within the introduction section. This discrepancy may be caused by a lack in the used list of physical simulation models ofsome neutron production channel (besides the photo- electronuclear processes) which is significant in the realevents.

A qualitative estimation of the absolute amount of particles participating in a real atmospheric discharge can bedrawn from following considerations. In the frames of hypothesis of a crucial role which play the cosmic ray particles of $10^{14}$-$10^{16}$eV EAS in lightning initiation [22, 23]the multiplicity of primary seed electrons $N_e$ which simultaneously can give a start to development of the multitude of partial avalanches inside the electrically chargedregion of a thundercloud must be of the order of showersize, i.e. $N_e \sim 10^5$-$10^6$for EAS of the said energies [33],and the great part of these particles must have the energy of the order of critical energy of the electromagnetic cascade theory (about 80 MeV in the air).According to figure 2, the particles with the energy of such an order mustgenerate an avalanche practically with 100% probabilitywhen coming into the region of field with the strength about runaway breakdown threshold $E_c$, so the sum multiplicity of the charged particles participating in dischargemust be of the order of $N_e \times$ hni, where hni is the mean particles number in a partial avalanche. The distributions from figure 5 predict the most probable multiplicities about $<n_e>\sim 2000 - 3000$ and $<n_\gamma>\sim 100$ correspondingly for electron and gamma ray components in a partialavalanche initiated by a 100 MeV seed particle. After multiplication, the sum multiplicity of discharge electrons occurs being about $\sim 10^9$, and that of the gamma ray quanta $\sim 10^8$. Analogous estimation for neutron component givesthe value about $\sim 10^6$. Because of their roughness and awide scattering of conditions in real thunderstorm events,all these estimations must be taken in the sense of lowerlimit.

Taking into account the tendency to anisotropy of angular distribution which is specific for electromagnetic components, and supposing the area of the emitting thundercloud region to be of the order of 1 km$^2$ (i.e. $10^{10}$cm$^2$),the total gamma-radiation flux from discharge area can be estimated as

$I = 10^8/10^{10}\text{cm}^{-2} = 0.01\ \text{cm}^{-2}$, andthis flux as a whole is concentrated spot like in a nearlyvertical direction. In this case, the number of signalsobtained from a gamma ray sensor of *Groza*experimentwhen detecting a discharge related radiation flash must be $n_\gamma \sim I \cdot S/\epsilon$, where $\boldsymbol{S}$ is the detector sensitive area, and $\epsilon$ - its registration efficiency. Taking the typical values as $\boldsymbol{S}/\epsilon \sim (300/0.5)\ \text{cm}^2$[31] the resulting amount of detectorpulses $n_\gamma$ must be about 1-10. This is just the case oftypical experimental measurements like [2] and [3] which have been routinely obtained at Tien Shan station. Hence,in spite of its roughness the result of present estimation is quite reasonable.

Similar estimations concerning neutron component leadto resulting neutron flux about $10^{-5}\text{cm}^{-2}$at observation level, and to signal multiplicity about $n_n \sim 0.1$ pulses froma neutron detector (for isotropic angular distribution of theneutron avalanche component, and for a typical effectivearea of neutron detector about 1000 $\text{cm}^2$). In reality, bythe measurements with enhanced time resolution the number of neutron signals frequently occurs quite comparablewith that of gamma ray, i.e. of some units or tens of neutron pulses registered from a single atmospheric discharge[12]. This contradiction may be another sign of essentialdiscrepancy between the models of neutron generation accepted at simulation procedure and with what does takeplace in real events.ϵ

**Conclusion.** The program code for as far as possible complete simulation of the processes of particle acceleration inside a large-scale atmospheric electric field region was createdinthe frames of *Groza* experiment. The program is basedonthe*Geant4* simulation toolkit and takes into account thespecific environmental features of the Tien - Shan mountain station. The simulation results concerning observable parameters of the electromagnetic component of particleavalanche agree well with the data both of theoretical andexperimental studies of avalanche development in atmospheric electric fields. This is an evidence of adequacyofthe set of physical models put into simulation, and gives the reason for using the described program code by furtherquantitative analysis of experimental results.

From the practical point of view, the simulation resultsconcerning an extremely anisotropic angular distributionof the electromagnetic avalanche components, and their limited path by realistic atmospheric conditions mean thatfor effective registration the active region of a thundercloudmust occur just above, and as close as possible to detector system. Also, a large scattering must be expected inpractise between the results obtained even in similar environment at different thunderstorm times. For precise registration of the time profile of excessive electromagneticradiation from an atmospheric discharge the resolution ofdata acquisition system must be at least of the microsecond order.

At the same time, the intensity of neutron flux predictedby simulation seems to be significantly below the existingexperimental data. This can be an indication of eitheran existence in real thunderstorm events of some unaccounted additional channel of neutron generation, besides the mechanisms of photo- and electron production whichhave been included into simulation physics list, or thiscan be a sign of an extremely high influence of electromagnetic interference on electronics of neutron detectorsfrom nearby electric discharges which mask or imitate the real neutron signal.Correspondingly, the design of neutron detector system for the next measurement seasons atTien - Shan now is greatly modified with special attentionpaid to its electromagnetic shielding. On the other hand,the very fact of a possibility to exist for some effective mechanism of neutron generation in natural atmosphericdischarges, besides any intermediate electromagnetic channel, is quite interesting in itself, and this problem remainsopen for further experimental investigations at Tien–Shanstation.

In spite of low intensityprediction whichresultsof simulation, the registration of neutron signal may occurmorepreferable at a distance of some kilometers from theactive thundercloud region than that of the electromagnetic components, due to more uniform angular distribution and prolongedlife time of emitted neutrons. Becauseof latter circumstance, any data acquisition system usedfor neutron registration must have a rather long samplinginterval, at least of the order of some tens of millisecondsafter a primary lightning trigger signal, and a microsecond scale time resolution.

**А. Л. Шепетов[1], Т. Х. Садыков[2], К. М. Мукашев[3], Л. И. Вильданова[4], А. Д. Мурадов[3], О. А. Новолодская[2], М. Е. Алиева[5]**

[1]Ресей ғылым академиясы, П. Н. Лебедев ат-ы Физика Институты, Москва, Ресей,
[2]Физика-технологиялық институты, Алматы, Қазақстан,
[3]әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан,
[4]Ғарыш сәулелерінің Тянь-Шань биік таулы ғылыми станциясы, Алматы, Қазақстан,
[5]Абай атындағы Қазақ ұлттық педагогикалық университеті, Алматы, Қазақстан

## GEANT4 ПРОГРАММАСЫ НЕГІЗІНДЕ КҮН КҮРКІРЕУГЕ БАЙЛАНЫСТЫ ТУЫНДАЙТЫН ЭЛЕКТРОН-ФОТОН АҒЫНЫН ЖОБАЛАУ

**Аннотация.** Тянь-Шань биік таулы кеңістіктігінде орналасқан ғарыштық сәулелердің ғылыми зерттеу станциясының деңгейінде ауқымды электр өрісінде туындайтын электрон-фотон ағынының дамуын модельдеуге арналған Geant4 инструментарилық программа құрылды. Бұл инструментарий Гроза программасы аумағында өндірілген эксперименталдық нәтижелерді талдау және жоспарлау мақсатымен дайындалды. Тасқынды процестің электромагниттік құраушыларын моделдеуге байланысты болжаунәтижелері: электрондық құраушының гамма-сәулелеріне қарағанда салыстырмалы қарқындылығы 30:1 еседей жоғары, олардың энергетикалық спектрлері (30-10000 кэВ аралығында дифференциалдық индексі 1,5–2 дәреже шамасындағы функция), бұрыштық таралуы теориялық және бұған дейін таулы деңгейде өндірілген эксперименталдық нәтижелерге сәйкес келеді. Болжау арқылы табылған гамма-сәулесінің эмиссиясы $10^2$ см$^2$ Тянь-Шань станциясы деңгейінде анықталған тікелей өлшеу нәтижелеріне тұспа-тұс. Сондықтан күннің күркіреуінен туындайтын шынайы құбылыстарды имитациялық модель арқылы болжау нәтижелері шындыққа сәйкес келеді деп санауға негіз бар. Дегенменде, болжау барысында көрсетілген нейтрондар ағыны шамасы жағынан эксперимент нәтижелерінен он шақты есе төмен екендігі байқалды. Оның себебін табиғи атмосфералық разряд кезінде пайда болатын нейтрондардың моделдеу кезінде қолданыс тапқан электромагниттік фотоядролық және электронядролық әсерлесулерден басқа да ескерілмеген механизімінің орын алуымен түсіндіруге болады. Сонымен қатар, моделдеу нәтижелерін негізге алу арқылы биік тау деңгейінде күннің күркіреуіне байланысты туындайтын түрлі сәулелерді зерттеуге қолайлы эксперименталдық қондырғыларды жобалау мәселесі де қарастырылады.

**Түйін сөздер:** күннің күркіреуі, найзағай, атмосфералық электр, қашқын электрондар, моделдеу, Geant4 жобасы.

**А. Л. Шепетов[1], Т. Х. Садыков[2], К. М. Мукашев[3], Л. И. Вильданова[4], А. Д. Мурадов[3], О. А. Новолодская[2], М. Е. Алиева[5]**

[1]Институт физики им. П. Н. Лебедева РАН, Москва, Россия,
[2]Физико-технический институт, Алматы. Казахстан,
[3]Казахский национальный университет им. аль-Фараби, Алматы, Казахстан,
[4]Тянь-Шаньская высокогорная научная станция космических лучей, Алматы, Казахстан,
[5]Казахский национальный педагогический университет им. Абая, Алматы, Казахстан

## МОДЕЛИРОВАНИЕ РАЗВИТИЯ ЭЛЕКТРОННО-ФОТОННОЙ ЛАВИНЫ В АТМОСФЕРЕ ОТ ГРОЗОВЫХ ТУЧ С ПОМОЩЬЮ ПРОГРАММЫ GEANT4

**Аннотация.** На основе инструментария Geant4 была разработана специальная программа для моделирования развития электронно-фотонной лавины в электрическом поле большого размера в типичных условиях окружающей среды Тянь-Шаньской высокогорной научной станции космических лучей. Этот инструментарий предназначен, в частности, для планирования и анализа экспериментальных результатов, полученных в рамках программы Гроза. Основные предсказания моделирования относительно электромагнитных компонентов лавины: относительное превышение интенсивности электронной компоненты над гамма-лучами (30: 1), их энергетические спектры (примерно, форма степенного закона с дифференциальным индексом -1,5-2 в диапазоне 30-10000 кэВ), а анизотропия их угловых распределений находится в хорошем согласии с результатами теоретических и экспериментальных исследований, которые были получены до этого в горных условиях. Прогнозируемое значение эмиссии гамма-излучения порядка $10^2$ см$^2$ на уровне наблюдения также достаточно хорошо соответствует прямым измерениям, выполненным на станции Тянь-Шань. Эти данные подтверждают адекватность используемой имитационной модели для реальных событий грозы. В то же время предсказанные нами лавинные нейтроны, по-видимому, на порядок недооценены по сравнению с данными соответствующих экспериментальных измерений; такое грубое несоответствие может быть свидетельством существования некоторого эффективного механизма генерации нейтронов в естественных атмосферных разрядах, помимо полностью электромагнитных фотоядерных и электрон-ядерных взаимодействий, которые были применены в моделировании. Обсуждаются требования к проектированию экспериментальных установок, подходящих для изучения грозовых излучений на высоте горы, которые следуют из представленного моделирования.

**Ключевые слова:** гроза, молния, атмосферное электричество, убегающие электроны, моделирование, программа Geant4.

**Information about authors:**

Shepetov A.L., P. N. Lebedev Physical Institute of the Russian Academy of Sciences (FIAN), Moscow, Russia; ashep@www.tien-shan.org; https://orcid.org/0000-0002-5521-1855

Sadykov T.Kh., Institute for Physics and Technology, Almaty, Kazakhstan; turlan43@mail.ru; https://orcid.org/0000-0002-4349-4616

Mukashev K.M., Al-Farabi Kazakh national university, Almaty, Kazakhstan; mukashev.kms@gmail.com; https://orcid.org/0000-0002-0516-8983

Vildanova L.I., Tien Shan Mountain Cosmic Ray Station of FIAN, Almaty, Kazakhstan; luvild@mail.ru; https://orcid.org/0000-0001-8558-9026; https://orcid.org/0000-0001-8558-9026

Muradov A.D., Al-Farabi Kazakh national university, Almaty, Kazakhstan; abyl.muradov@gmail.com; https://orcid.org/0000-0002-7052-8228

Novolodskaya O.A., Institute for Physics and Technology, Almaty, Kazakhstan; novololga@yandex.ru; https://orcid.org/0000-0002-1978-2781

Alieva M.E., Abai Kazakh national pedagogical university, Almaty, Kazakhstan; moldir-2008@mail.ru; https://orcid.org/0000-0003-0440-6211

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