1. Introduction

The high-energy emissions of electrons, gamma rays and neutrons produced in association with lightning and thunderclouds have been observed in a number of space and ground-based experiments. Elucidation of the mechanisms of high-energy radiation arising at the time of atmospheric discharge is an increasingly expanding area, both of experimental and theoretical research. A comprehensive review of the physical phenomena occurring in the thunderstorm atmosphere is presented in [1] where this field of study comes under the designation of ‘high-energy atmospheric physics’.

Of particular interest are occasional observations of temporary enhancement of the neutron flux inside thunderstorm atmosphere, which could be due to nuclear reactions caused by the neutrons produced inside a strong electric field. The first evidences of a surplus neutron radiation at thunderstorm time have been reported in [2]. In recent years, some papers discuss the possibility of neutron generation in connection with powerful lightning discharges on the basis of experimental observations made at mountain heights at Tien Shan [3, 4], Aragats [5, 6], Tibet [7], as well as at the sea level in MSU [8] and Yakutsk [9]. To date, different physical mechanisms have been discussed for the explanation of thunderstorm-related neutron production, but the nature of this phenomenon still remains unknown.

Recently we reported our first measurements of neutron emission originated by atmospheric lightning-like discharge in a laboratory installation [10]. Experiments were carried out inside an electric field with the average strength of the order of $\sim 1 \text{ MV} \cdot \text{m}^{-1}$ and with neutron detectors of two independent kinds: the CR-39 type tracers and the plastic scintillators. Tracers were placed inside anode and cathode electrodes. They registered neutrons within the range from thermal energies up to the energies above 10 MeV. The estimations of the average density of neutron flux lay in the range of $(10^5 - 10^6) \text{cm}^{-2}$ per discharge shot. We did not find any convincing explanation for observed high values of neutron flux according to the registration in the CR-39 track detectors. Signals from plastic scintillation detectors placed inside a Pb box of 10 cm thick was considered as created by fast neutrons. It was found that the neutron generation takes place at the initial phase of electric discharge and is correlated with the generation of x-ray radiation. The maximum observed flux of fast neutrons in a single shot is estimated at the level of up to $1 \times 10^5$ neutrons in $4\pi$ sr.

A detailed theoretical analysis of various nuclear reactions which could contribute to this flux is presented in [11], and it
ends with the conclusion that the ‘known fundamental interactions cannot allow prescribing the observed events to neutrons’. Insufficient knowledge on physical processes, which could take place at the initial stage of the atmospheric discharge and the complexity of any self-consistent numerical simulation of this phenomenon, determines the need for a comprehensive experimental study of the formation of the discharge and diagnosis of different accompanying radiations. The use of a laboratory installation with its parameters sufficient for a precise temporal and spatial separation of running processes allows us to establish general laws and to check the expected hypothesis on discharge formation. In the present article we report the new results concerning the detection of neutron emission from a controlled electric discharge in the air, which was made with a combination of plastic scintillation detectors and $^3$He-filled proportional ionization counters of thermal neutrons. This study has revealed a more sophisticated temporal structure of the neutron bursts observed at the time of electric discharge. It was found that the flash of hard x-rays generated by discharge is not always accompanied by any appearance of neutron signal, and both the single and multiple neutron pulses were recorded, which do not overlap with any x-ray pulses at all. In some rather rare events the neutron pulses appear at the final stage of discharge, when the voltage has just fallen down to zero.

2. Apparatus layout, calibration and simulation

Experiments were held with a high current electron accelerator ERG destined for investigation of the high-voltage discharge in the air [12]. The main characteristics of generated discharge and the procedure of electrophysical diagnostics were the same as in the measurements described in [10]. High voltage pulses with $\sim 1$ MV amplitude were applied to a discharge air gap of the 450–750 mm width (the latter was changed in various runs). The current pulse amplitude was about 10–12 kA, and the total duration of pulses was about $\sim 350–1000$ ns, depending on the gap width. The scheme of the system and the current experimental set-up with a set of plastic scintillation detectors, the $^3$He-filled thermal neutron counters and optic sensors is shown in figure 1.

In successive experimental series, electrodes of different configurations were used: a cathode and anode of hemispherical shape, 80 mm and 90 mm in diameter, and the hemispherical $\varepsilon 90$ mm mesh anode. As a cathode we used a polished TiN-coated carbon steel needle of 0.6 mm in diameter also (see figure 2). The tip radius of the needle was about 50 microns in the initial ‘fresh’ state, slightly increasing to about a hundred microns as the electrodes wear.

In both experimental series, one and the same assembly of three plastic scintillation detectors (SD1–SD3) was used, which is shown in positions I and II in figure 1. All detectors were built on the basis of $15 \times 15 \times 5$ cm$^3$ scintillator blocks optically coupled with the FEU30 type photomultiplier tube; the detector SD1 was shielded with a 10 cm thick wall of the stacked lead bricks from all its sides (even at 100-fold attenuation of gamma radiation threshold energy it is approximately $E_\gamma \approx 2$ MeV). SD2 was wrapped by the two layers of sheet lead with the sum thickness of 6 mm (which corresponds to a gamma ray cutoff energy $E_\gamma \approx 200$ keV). SD3 was covered by aluminum foil with the thickness of 50 $\mu$m (cutoff energy $E_\gamma \approx 10$ keV).

Location I of the scintillation assembly was used in most of the experiments. In this position, the SD1 detector was placed at the distance of 100 mm from the axis of the system and 470 mm behind the anode; SD2 was just on the axis and at the distance of 470 mm from the anode; and SD3 was at the distance of 880 mm from the anode and 110 mm aside the axis, and below the level of SD1 by the values of its height. The position II was used to measure the weakening of radiation intensity and to estimate its energy in supposition if all generated emission is considered as gamma rays. In second position all SDs were located in one vertical plane, 900 mm aside of the discharge axis and the detector SD3 was placed between SD1 and SD2.

All three scintillation detectors were calibrated with a standard x-ray source RINA [13] and have approximately one and the same sensitivity relative to electromagnetic radiation. The x-ray tube of IMA6 D type powered by 0.15 J pulses with the peak voltage of 100 kV. The angular divergence of x-rays is 30$^\circ$ and the pulse duration is about 10 ns with a repetition rate of 8 Hz. The diameter of the effective focal spot is 2.5 mm.

For continuous (not pulsed) mode estimation, their registration efficiency relative to neutron flux, the scintillation detectors were irradiated by a $^{252}$Cf neutron source with an overall yield of $3 \times 10^4$ neutrons per second. In the case where the source is placed in the center point of the scintillator plane the detection efficiency of the detector was 0.17. When the scintillation detector was placed inside a 10 cm lead box and the source was at the anode (at a distance of about 0.5 m) the scintillator cannot record the signal (background level) because of the small average intensity of neutron flux from the source.

As an independent method of neutron registration in the present experiment was applied, the multichannel detector on the ionization neutron counters. This detector is based on the $^3$He-filled neutron counters of the SNM-18 type, which were operating in proportional mode. Twelve $\varnothing 3 cm \times 30$ cm counters together with all necessary electronics were put into a 2 mm thick duraluminum casing covered by the discharge (front) side with a 7 cm thick paraffin layer for the moderation of anticipated neutrons. The total area of the neutron detection block is $1000 cm^2$; the counters are filled with the pure $^3$He gas under the pressure of 2 atm. When operating, the detector was placed in position at 70 cm from the anode and 130 cm from the cathode as shown in figure 1, with its front moderator cover being turned against the generator. The pulses from all neutron counters were recorded separately, so the average intensity of neutron flux could be calculated as a sum of these counts.

When using the ionization counter-based detectors in the vicinity of a powerful electrical installation, it is a general problem to suppress the strong electromagnetic interference on their counts from the nearby electric discharges. Therefore, the neutron counters together with their signal acquisition...
Electronics were especially locked inside an electrically shielded volume. Also, in a part of the experiments the whole counter assembly was placed inside a tight box of welded 3 mm thick iron, and in this position another 43 mm thick layer of light material (perplex)—a neutron reflector—was put against the back side (opposite to discharge generator) of the counter case.

Absolute calibration of the neutron detector was made experimentally with the use of the $^{252}$Cf neutron source. With the source placed in the vicinity of the cathode, the net neutron detection efficiency of described 3He counters assembly occurred to be 0.076%, and with the source in the anode region—0.12%.

Besides these experimental measurements, efficiency of neutron registration was defined in complete simulation of the neutron propagation process both inside the neutron detectors and in surrounding materials with the use of the Geant4 toolkit [14]. For this purpose, three detector models were built, which took into account specific features of detector set-ups used in reality (see figure 3).

The model I corresponds to the typical configuration of the SD1 scintillation detector: a $15 \times 15 \times 5$ cm$^3$ plastic scintillator block surrounded by 10 cm thick lead walls. In model II a set of 12 $^3$He-filled cylindrical ‘counters’ having the size of a real SNM-18 type detector (3 cm in diameter and 30 cm long) were put into a box of Al material with a 7 cm thick paraffin moderator layer placed at its front side. In model III this counter assembly was supplemented with a backward neutron reflector of 4 cm thick perspex, and the whole set-up was placed inside a solid metallic box of 3 mm thick iron sheets. The particle physics module of the simulation program took into consideration the following processes of neutron interaction: the Geant4 models of elastic coincidences in the range from thermal energies (of the order of $10^{-2}$ eV) up to 4eV,
as well as the elastic coincidence models of the intermediate (4 eV–20 MeV) and high-energy neutrons (above 20 MeV); the models of inelastic interaction in the ranges of thermal, intermediate and high energies; the models of radiative neutron capture. For the protons, besides analogous processes of their elastic and inelastic interactions, the models of multiple scattering and ionization losses were considered, and for the positive and negative pions the decay process (the physics of negative pions included also the process of their absorption at rest). The fact of neutron registration was signaled either by the appearance of any charged particle (mostly, a recoil proton) with the energy above 0.5 MeV inside the scintillator volume of the model I, or by a $^3$H nucleus born inside the volume of any neutron counter for the case of models II and III (correspondingly to nuclear reaction $n + ^3$He $\rightarrow p + ^3$H which is used in the real SNM-18 type detectors). In turn, the overall efficiency of neutron registration was defined as a relation of the number of ‘registered’ neutrons to the total number of primary particles put into simulation.

Three distribution variants of primary neutron particles were accepted in the simulation series for every detector model, I, II and III. In the first turn, a parallel beam of monoenergetic primary neutrons was falling on the center point of the detector front perpendicularly to its surface (an ideal case of primary geometry and the upper limit of possible registration efficiency). In the second (intermediate) variant the position of primary neutrons was randomly selected on the front surface while their momenta remain always perpendicular to it. In the third (realistic) simulation the primary neutrons were emitted with isotropic direction distribution from a spherical point source displaced 70 cm apart from the front surface, similarly to the geometry of the real experiment where the origination of neutrons is supposed to have a place somewhere around the electrodes of the high voltage generator. A number of succeeding simulation runs with constantly increasing energies of primaries was fulfilled for every combination ‘detector model/primary geometry’, and a set of registration efficiency distributions was calculated with dependence on neutron energy. These results are presented in figure 4.

According to the upper frame of figure 4, the maximum average efficiency of neutron registration by scintillation detector in the energy range of some MeV must be confined by the curves 1 and 2, i.e. somewhere between 5–20%. For the ‘realistic’ configuration of a distant isotropic neutron source the curve 3 predicts an efficiency of about 0.4–0.5%.

The simulation results made for a ionization neutron counter-based detector in the middle and bottom frames of figure 4 have rather irregular behavior in the MeV energy range for the case of a distant point source (the curve 3). This can be explained through the manifestation of an additional neutron multiplication mechanism due to the recoil process in the surrounding materials around the neutron counters; this effect starts to be feasible just around the MeV energy threshold and occurs as being noticeable in the curves 3 because of their generally low efficiency level.

In the case of the neutron detector model II the simulation predicts the mean registration efficiency of about 0.15–0.20% for a distant primary source (curve 3), which is close to a 0.12% efficiency measured with the location of the californium source in the anode region. The presence of the additional backward neutron reflector in the case of model III reveals itself through the increase of the resulting registration efficiency up to the values of 0.30–0.45%.

Discharge development in the real-time was controlled by its photographing at different angles with the use of a multichannel digital photo-recorder and the application of the neutral and colored optical glass filters, and through the fast oscilloscope recording of characteristic electric parameters and radiation intensities.

3. Neutron and x-ray measurements in the conventional discharge

The lightning discharges are recorded simultaneously with neutrons and gamma radiation using scintillation detectors. The detection of neutrons and/or hard gamma rays in a
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A laboratory experiment requires a clear analysis. Firstly, we have identified a strong dependence of the appearance of the hard (neutron or gamma) radiation from the electric field strength near the electrodes, which is determined by their form. Statistics of events with the advent of x-rays and neutrons are presented in table 1.

Secondly, we investigated in detail the temporal structure of the appearance of neutron pulses. In a previous paper [10] we noted that the momentum of the neutron radiation, the detected scintillation detector placed behind a lead shield, is correlated with the occurrence of x-ray pulses and is located within it. That is, the neutron pulse was observed in the initial ‘dark’ phase of the discharge until the closure of the cathode and anode streamers. However, the structure of the neutron pulse was more complicated.

New measurements have shown that the structure and characteristic relative arrangement pulses of x-rays and neutron radiation has been quite diverse (figure 5). The emergence of x-ray radiation is not always accompanied by the appearance of neutrons (figure 5(a)). The most common occurrence of neutron pulses clearly correlated with the x-ray pulse and is located inside (figure 5(b)). Both the single and binary neutron pulses inside the x-ray are recorded (figures 5(c) and (d)), and near the x-ray pulses (figure 5(e)). In some rare cases, the neutron pulse appears at the final stage of the discharge (figure 5(f)) in the absence of x-ray radiation. In most cases, the neutron pulses occur near the peak voltage to the main phase of the discharge (at the peak of pre-pulse current). In figure 5 traces of x-rays registered by SD3 covered by aluminum foil with the thickness of 50 μm (cutoff energy $E \approx 10$ keV) are shown.

However, there are cases where the neutron pulse is generated at the beginning of the main phase (figure 6(a)) (after closing discharge gap) or at the peak of the discharge current and correlated with the x-ray pulse (figure 6(b)). In figure 6, unlike figure 5, instead of the initial part (pre-pulse), the total discharge current form is shown.

Various provisions of the neutron radiation pulse relative to the pulse voltage and discharge current leads to the assumption of different possible mechanisms of neutron generation in the initial stage of discharge (until the end of the streamer-leader stage) and its main stage.

The amplitude of the neutron signals in a variety of shots can vary by an order of magnitude. Taking into account the

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Figure 4. Efficiency of neutron registration with different detector types used in the present experiment (result of Geant4 simulations). From top to bottom frames: the scintillation neutron detector inside a lead shielding assembly (detector model I); the set of ionization neutron counters with the 7 cm thick neutron moderator before its front side (model II); the same set of counters together with its front-side moderator and back-side reflector put in an iron box (model III). Curves 1 correspond to simulation for a normal beam of monoenergetic primary neutrons hitting the center of the detector’s front side (ideal case); 2—for the neutrons distributed randomly over detector front with their momenta perpendicular to the surface; 3—for a point-like isotropic source of primary neutrons displaced 70 cm apart from the front surface (realistic case).
efficiency of the neutron detection by the scintillation detector, maximum observed flux of fast neutrons in a single shot can be estimated at the level of up to \(1 \times 10^5\) neutrons in \(4\pi\) sr according to our previous results [10].

Of course, a hypothetical possibility of high-energy gamma ray generation cannot be rejected completely. It can penetrate through a Pb shield that is 10 cm thick. Therefore, we also used data on multiplicities weakening wide beams of gamma radiation for the 10cm protection of Pb [15] to distinguish neutron and gamma radiations. Figure 7 shows the waveform of the pulses detected by all three scintillation detectors placed in position II (see figure 1). In figure 7(a) the ratio of the amplitudes of the signal on the waveform SD3/SD1 ≈ 10 and ratio of the amplitudes SD2/SD1 ≈ 6. Both ratios correspond to

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**Table 1.** Statistics of events with the advent of x-rays and neutrons.

| Geometry of the electrodes and the total number of shots | Shots with x-ray (>10 keV)(SD2) | Shots with x-ray (>100 keV)(SD3) | Shots with neutron pulses (SD1) |
|----------------------------------------------------------|---------------------------------|---------------------------------|-------------------------------|
| Hemishpere (cathode)-hemishpere (anode) usual discharge   | 341 (100%)                      | 133 (39%)                       | 5 (1.4%)                      |
|                                                          | 96 (100%)                       | 35 (36%)                        | 3 (2%)                        |
| Needle (cathode)-hemishpere (anode) usual discharge      | 950 (100%)                      | 827 (87%)                       | 143 (15%)                     |
|                                                          | 20 (100%)                       | 18 (92%)                        | 3 (15%)                       |

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**Figure 5.** X-rays and neutron radiation pulses relative to voltage and pre-pulse current traces.
Figure 6. X-rays and neutron radiation pulses relative to voltage and total current traces.

Figure 7. Traces of x-rays of different energy and neutron radiation relative to voltage and pre-pulse current traces.

Figure 8. Two illustrations of simultaneous detection of neutrons with scintillation detectors (left) and the $^3$He-detector (right). The upper panel corresponds to the detection of neutrons at the initial stage of the discharge and the lower panel—at the final stage.
the energy of gamma rays $E_\gamma > 10 \text{ MeV}$, which is an order of magnitude more than ‘applied voltage’ 1 MeV.

Since the emission spectrum is not known, an estimate gives a lower bound. Therefore, with high probability we can assume that this signal (with SD1) is formed by fast neutrons but not gamma rays. Most experiments with laboratory discharges give the energy of gamma rays at a level of 150–200 keV [16–19], which is consistent with the results of our measurements. At the same time, for another shot (figure 7(b), which is very similar to figure 7(a)) of this run, the signal from SD1 is absent and the ratio of the amplitudes SD3/SD2 ≈ 2.5. It corresponds to the energy of gamma rays $E_\gamma > 0.5 \text{ MeV}$ in all.

To confirm these findings, a $^3$He-detector was used. Figure 8 shows the correlated events, when the neutrons produced per one shot at a time as recorded by scintillation detectors and the $^3$He-detector. The left column shows the waveform from the scintillation detectors, the right column shows the waveform of the sum signal from the comparator of the $^3$He-detector (1 block, 12 tubes). The first panel shows a case where the scintillation detector detects a neutron signal of large amplitude, which lies inside the x-ray pulse (left) and a series of neutron pulses recorded the $^3$He-counters (right). The second panel in figure 8 corresponds to the case in which there is a neutron signal of large amplitude in the scintillation detector at the final stage of the discharge and recorded neutrons in the $^3$He-counters. Table 2 shows data for all the shots in which neutrons were detected by scintillation detectors and neutron counters. Experiments have been carried out in a configuration semispherical mesh anode of 90 mm and a cathode needle.

| Total shots | Shots with x-ray (>10 keV) | Shots with neutrons on SD (10 cm Pb) | Shots with neutrons on $^3$He-counters |
|-------------|-----------------------------|-------------------------------------|--------------------------------------|
| 340 (100%)  | 296 (87%)                   | 35 (10%)                            | 44 (13%)                             |

4. Observation of radiations in an interrupted discharge

Finally for a detailed study of radiation in the initial leader-streamer or dark phase of the discharge a series of measurements were carried out, in which especially not a complete discharge formed. For this purpose, the cathode is installed by a radial rod of adjustable length with a groove which develops on the outer cylindrical discharge electrode (anode). By varying the length of the rod, it is possible to switch the current from the main (longitudinal) groove on the discharge gap at a preset time interval, thus interrupting the discharge development in the usual longitudinal direction. Experiments on the production of the integrated image of the initial phase of atmospheric discharge by interrupting the longitudinal discharge when current switching to radial discharge were carried out for two variants of electrode geometry: a cathode and an anode in the form of a hemisphere with a diameter of 90 mm and a semispherical anode and cathode needle.
Integral photos and corresponding data of usual axial and interrupted discharges are shown for the variant of electrode geometry with a semispherical anode and cathode needle. Amplitude of the voltage pulses was about the same ~1 MV. The total duration of voltage pulse of the interrupted discharge decreased almost twice. In the first case, it was 96 shots, of which 34 shots of x-rays with photon energies above 100 keV and only 2 pulses of neutrons have been recorded (See table 1). In the second series were only 20 shots. In each of these shots x-ray photons with energies above 100 keV were recorded and three shots had pulses of neutrons. That is, the relative quantity of the shots with gamma rays of defined energies are practically the same as usual as for interrupted discharges (see table 1). Therefore, we can conclude that the radiation shown in figure 9(d) formed incomplete discharge in the longitudinal gap configuration as shown in figure 9(c).

5. Conclusion

New data using various combinations of scintillation detectors and neutron ^3^He counters fully confirmed the neutron radiation in a laboratory atmospheric discharge. The main goals of the paper were: to confirm neutron generation in high voltage discharge; to give a more accurate quantitative estimate of neutron yield; to note the conditions when the effect is observed essentially more often. After analyzing large discharge statistics, we have established a strong dependence of the hard x-ray and neutron radiation appearance on the shape of the electrode. In the configuration of electrodes in which the anode and cathode is a hemisphere, in 33% of the shots hard x-ray radiation has been found and only 1.4% of the shots have been registered as neutron radiation. In the configuration of the electrodes in the form of a hemispherical anode and cathode needle appearance emissions were significantly more likely to have hard x-ray radiation appear in 87% of the shots—and neutron emission—in 15% of the shots. In this study, we focused on the temporal structure of neutron bursts at the time of discharge. Discovered in previous work the appearance of neutrons in the initial ‘dark’ phase of the discharge was confirmed, however, the temporal structure of neutron radiation generation was much more diverse. This may indicate different mechanisms for generating penetrating radiation during the formation and development of the atmospheric discharge. Direct evidence for the detection of neutron radiation was obtained with the use of ^3^He neutron counters and the analog recording of neutron pulses generated at the time of discharge. The close coincidence of measured and calculated neutron detection efficiencies of ^3^He-counters, allows us to estimate the maximum value of the flux of neutrons emitted in shots at \( 1 \times 10^3 \) to \( 5 \times 10^4 \) in \( 4\pi \) sr, depending on the place of neutron generation (near the anode or near the cathode, respectively). With such small flows it is very difficult to talk about isotropic radiation, so the real overall neutron flux may be even less. Indirect evidence of this statement can serve the shots in which the neutrons are recorded by scintillation or the ^3^He detector.

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