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Thunderstorm neutrons

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Contents

Abstract. **To assess the current state of studies of nuclear reactions in thunderstorms, observational data are reviewed on the neutron flux enhancement in thunderclouds and during thunderstorms related to photonuclear reactions because of the bremsstrahlung of the avalanches of high-energy runaway electrons that can develop in thunderstorm electric fields. Selecting thunderstorm neutrons is a challenging problem, since detectors are affected by a mixed field of various penetrating radiations that also includes, apart from neutrons, primary high-energy electrons and their bremsstrahlung. Special attention is given to the discovery of the electron–positron annihilation line with the photon energy of 0.511 MeV in a thundercloud and on Earth's surface during thunderstorms, providing trustworthy evidence of neutron production by thunderstorms and the photonuclear origin of thunderstorm neutrons. The consequences of this discovery are discussed.**

Keywords: thunderstorm atmosphere, high-energy electrons, bremsstrahlung gamma rays, nuclear reactions, neutrons, positrons, annihilation

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"*New is a carefully forgotten old.*"
Favorite proverb of Dr L V Tarasova from VNIIEF, who was the first to detect high-energy runaway electrons and their bremsstrahlung in electric discharges in the open atmosphere [1, 2].

1. Introduction

The problem of thunderstorm neutrons is related to high-energy atmospheric electricity — a field of geophysics that is relatively new although having almost age-old history. It is new judging by the number of publications reporting the results of experimental and theoretical studies of high-energy processes and phenomena in thunderstorm atmosphere, the growth of which began in 1980s, was slow in 1990s, and became fast in the new century. However, the research in the field of atmospheric electricity of high energies started at the end of the first quarter of the last century by a publication of two hypotheses by the Scottish physicist and meteorologist Charles Wilson [3]. Now a widely known hypothesis, predicting electron acceleration ('runaway' [4]) to high energies in the electric fields of thunderclouds has been proven by direct observations of accelerated electrons and their bremsstrahlung in the X-ray and gamma ranges [5–49]. Two kinds of emission, differing by their duration, have been discovered. First, thunderstorms produce bright sub-millisecond gamma-ray bursts with photon energies up to a hundred MeV [39]. These events, unexpectedly discovered in near space by Fishman et al. [7] during the Burst and Transient Source Experiment execution aboard the Compton Gamma-Ray Observatory in the early 1990s, are now called terrestrial γ-ray flashes (TGFs). TGFs are associated with thunderstorms and, in particular, with electromagnetic pulses (EMPs) of lightning discharges. TGFs tend to occur near the upper regions of thunderclouds, as confirmed in TGF events associated with upward propagating intracloud

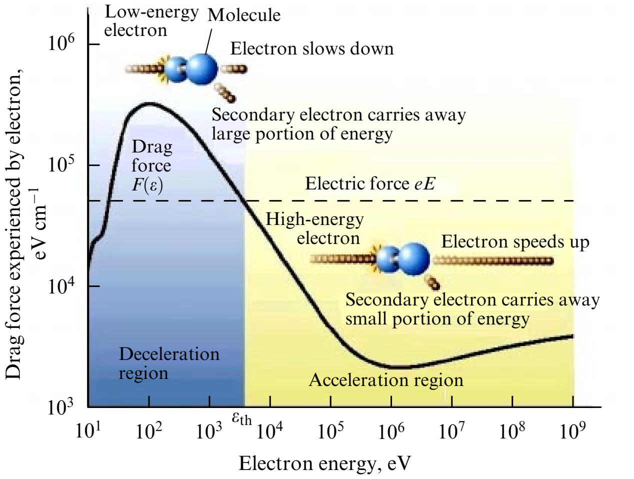

Figure 1. Runaway electron scheme in air [52, 53]. Solid line is the dependence of the electron drag force on the electron energy under STP conditions, dashed line is the electric force, ε_{th} is the runaway energy threshold.

discharges [50, 51]. Another kind of high-energy emission is so-called 'γ-ray glows' [18, 19], associated with processes in thunderclouds, i.e., rather prolonged pulses of X-ray and γ-ray emissions lasting from fractions of a second to tens of minutes, seen on the ground and inside or near thunderclouds from aircraft and balloons [5, 6, 8–10, 19, 22, 28–31, 33, 45].

The mechanism of the electron runaway process in homogeneous electric field E is illustrated in Fig. 1 [52, 53], where the drag force $F(\varepsilon)$ experienced by an electron with energy ε as a result of inelastic (ionization, excitation, radiative losses) interactions with air molecules is displayed. Using the continuous function $F(\varepsilon)$, conventional in the deterministic description, instead of stepwise energy losses experienced by the electron, in the range of low energies ($\leqslant$ 100 eV), naturally, is not correct, as the lost energy is comparable to the energy magnitude before the interaction. Curve $F(\varepsilon)$ is characterized by a maximum $F_{max} \approx 27$ MeV m^{-1} atm^{-1} in the vicinity of the energy $\varepsilon_{max} \approx 150$ eV and a minimum $F_{min} \approx 218$ keV m^{-1} atm^{-1} in the vicinity of $\varepsilon_{min} \approx 1$ MeV. Runaways are those electrons whose energy surpasses the magnitude ε_{th} (cf. Fig. 1) identified as the runaway threshold. In a mode with runaway electrons, the secondary electron, produced as a result of ionizing collisions of the primary (runaway) electron, carries away a small portion of the energy of the primary electron, such that the latter continues energizing. Allowing for the electron scattering in Coulomb collisions shifts the minimum position ε_{min} to the range of higher energies, to approximately 5 MeV, and increases F_{min} by 25% [49].

While analyzing X-ray amplifications they observed in the first half of the 1980s aboard aircraft in thunderclouds [5, 6], McCarthy and Parks [54] showed that Wilson's acceleration of primary electrons alone is not sufficient for explaining the measured magnitudes of X-ray fluxes. This difficulty was overcome after discovering a new process, theoretically predicted by Gurevich, Milikh, and Roussel-Dupré [55], in which primary high-energy electrons created in atmosphere by cosmic rays not only continue energizing (runaway [4]) in a thundercloud field, but, in rare ionizing events with the birth of secondary high-energy runaway electrons, multiply, forming a relativistic runaway electron avalanche (RREA). In the process by Gurevich–Milikh–Roussel-Dupré, in the range of energies significantly above the threshold ε_{th} (see Fig. 1), in ionizing collisions the energy of the primary electron is shared between the primary and secondary electrons in such a proportion that both electrons turn out to be runaways.

The concept of the RREA, developing in rather weak but extended thundercloud fields or in strong localized fields of a lightning leader, appeared very productive and now underlies both theoretical analysis and numerical simulation of high-energy processes in a thunderstorm atmosphere. It was modified with relativistic feedback, allowing the self-sustained development of the RREA due to its own secondary emissions (X-rays and γ rays, positrons) producing seed centers, from which new series of high-energy runaway electrons develop [48, 56, 57], as occurs in the low-energy range in the process of cathode-directed streamer development supported by the ionization of a gas ahead of the streamer front by its own radiation with photon energies above the ionization energy of the gas atomic particles [58, 59]. Nevertheless, "...a theoretical challenge remains to explain how so many high-energy electrons are generated in our atmosphere on such short time scales" as the TGF duration [19].

Less known is a prediction by Wilson of nuclear reaction occurrences in thunderclouds. The state of physics in the 1920s was such that Wilson, while developing his first hypothesis, was capable of executing only elementary estimations of the electron acceleration in thundercloud electric fields [3]. As to the nuclear reactions, Wilson merely specified the possibility of a disintegration or synthesis of nuclei of atmospheric species. As neutrons often occur among the daughter products of nuclear reactions, an observation of atmospheric neutron flux enhancement in a thunderstorm atmosphere would be direct evidence of occurrences of nuclear reactions. Attempts to check Wilson's first idea were being undertaken beginning in the early 1930s [60–68] (see reviews in [69, 70]). But, though the neutron was also discovered at that time [71], Wilson's second idea was outside the attention of the scientific community for decades.

Only a half a century after Wilson's publication, Libby and Lukens evaluated an expected neutron yield from a lightning channel [72] in connection with a possible contribution of thunderstorm neutrons in a production of the carbon isotope $^{14}_{6}C$, which was proposed for determining age [73] and now is widely used for the dating of archaeological artifacts and works of art. As natural water, along with the usual molecules H_2O, contains heavy-water molecules D_2O (0.015%) and HDO (0.03%), in which nuclei of hydrogen are replaced by those of deuterium, Libby and Lukens, proceeding from the idea that in lightning channels reactions of nuclear synthesis ($^2H(^2H,n)^3He$; energy of produced neutrons: 2.45 MeV) occur and, scaling the results of laboratory experiments with electric explosions of polyethylene threads enriched with deuterium [74], estimated the neutron yield $Y_{light} \approx 10^{16}$ per lightning discharge in a channel with a volume of 10 m^3 using an extremely simple formula, which does not allow for even the plasma temperature:

$$\frac{Y_{light}}{Y_{disch}} \approx \left(\frac{\rho_{light}}{\rho_{disch}}\right)^2 \frac{V_{light}}{V_{disch}} \frac{\tau_{light}}{\tau_{disch}}, \tag{1}$$

where ρ is the mass density, V is the volume, and τ is the lifetime of the lightning or laboratory pinch plasmas. Actually, the authors committed a computation error; the estimation with formula (1), using the same magnitudes of the quantities in it as in [72], underestimates $Y_{\rm light}$ by two orders of magnitude [69].

Fleisher et al. [75] cite the neutron yield from the lightning channel $Y_{\rm light} \approx 10^{12}$, referencing a private communication by Mosher, the co-author of the article [74], who executed more accurate scaling using a greatly overestimated cross section of the $^2H(^2H, n)^3He$ reaction obtained under the assumption of a tenfold excess of discharge plasma temperature $T_{\rm disch}$ in [74] over the plasma temperature $T_{\rm light}$ of the hottest part of the lightning channel. With a more realistic ratio $T_{\rm disch}/T_{\rm light} = 10^3$, according to the authors of Ref. [75], it is improbable that lightning plasmas are capable of generating measurable neutron numbers. Executing their own experiment with the goal of searching for neutron generation by discharges in the open atmosphere, which turned out to be unsuccessful, and scaling its results under the assumption that the limit fluence of neutrons from the laboratory discharge did not exceed the background magnitude, they decreased the evaluation by Mosher twentyfold.

In the first attempt to detect thunderstorm neutrons, executed by Fleisher in 1975 with solid-state nuclear track detectors, no evidence of increases in the track numbers during thunderstorms was observed [76]. Results of the first successful observations of thunderstorm neutrons were communicated in the early 1980s [77]. Since then, though, after a significant time lag (cf. [78]), from time to time, observations are reported of neutron flux amplifications in thunderclouds, in particular, during thunderstorms correlating with lightning EMPs.

Writing the given review is motivated by increasing interest in the production of neutrons by thunderstorms and the necessity to assess the status of the research in this area of the physics of high-energy atmospheric electricity, to evaluate if neutron production is a common process in the thunderstorm atmosphere, and to substantiate within the framework of the latest observations the photonuclear origin of thunderstorm neutrons as predicted in paper [79]. With this goal, observations of thunderstorm neutrons are reviewed. A difficulty in a trustworthy interpretation of obtained results is noted. Special attention is given to the observation results by Dwyer et al. [19] and Enoto et al. [46], who discovered the thunderstorm gamma line of positron–electron (e^+e^-) annihilation, which may be more reliable evidence of the generation of thunderstorm neutrons and their photonuclear origin than the data of a direct registration of neutrons. Consequences of this discovery are discussed. The review is limited to the available observation data; results of theoretical analyses and numerical simulations are only mentioned, if necessary.

2. Observations of neutron flux enhancements in thunderclouds and during thunderstorms

2.1 Registration by gas-discharge detectors

After the report by Shah et al. [77] published in 1985, mostly in the new millennium, papers have been published claiming statistically significant events of atmospheric neutron flux amplifications in thunderclouds and during thunderstorms in various areas of the globe [31, 33–37, 40–42, 45, 78, 80–86]. Most frequently, neutron monitors with boron BF_3 (reaction $^{10}B(n, \alpha, \gamma)^7Li$) [31, 33, 40–42, 77, 78, 83–86] or helium ^3He proportional counters (reaction $^3He(n, p)^3H$) [40–42, 82] are used to detect neutrons. The events of count rate increase, which are associated with thunderstorm neutron production, have been observed at different latitudes at sea level, in high-mountain settings, and in near space (Table 1). Some of these events are of a millisecond duration, like TGFs; the duration of the others is in the range of seconds and minutes, similar to gamma glows.

In experiment [77], in which the first evidence of atmospheric neutron flux enhancements correlated with lightning EMPs were obtained, delay times of neutron arrival at a detector relative to the EMPs were measured. The observations were carried out with the Lead-Free Gulmarg Neutron Monitor (LFGNM) operating at a high-mountain scientific research laboratory (Gulmarg, Kashmir, India). This is a Himalayan area at an elevation of 2,743 m a.s.l. (a.s.l. — above sea level) with severe thunderstorm activity (on average, 30 lightning strokes per day). The monitor comprises 21 cylinder boron counters with a total effective surface area $S_{\rm eff} \approx 3$ m^2. The recording electronics were triggered by lightning EMPs. Characteristic times of lightning discharges and recording electronics relate as follows: $\Delta t_{\rm str} \ll \Delta t_{\rm count} \ll \Delta t_{\rm is} \ll \Delta t_{\rm dead}$, where $\Delta t_{\rm str}$ is the lightning stroke duration, $\Delta t_{\rm count} = 320$ μs is the LFGNM counting time, $\Delta t_{\rm is} \approx 40$ ms is a typical inter-stroke interval, and $\Delta t_{\rm dead} = 400$ ms is the LFGNM dead time. The observations were carried out for three years till 1985; 11,200 lightning EMPs were registered, of which 10,818 were correlated with one detected neutron, 250 with two neutrons, and 124 with three or more neutrons (Table 2, Fig. 2). Shah et al. [77] believe that the one-neutron events are due to neutrons produced by cosmic rays; the two-neutron events are only partially due to cosmic rays, but the events with three or more detected neutrons should be totally attributed to thunderstorms.

Most frequently, multiple-neutron events occurred with the lowest time delays, distributed in the range 10–50 μs (Fig. 2), which is consistent with the typical lightning stroke duration $\Delta t_{\rm str} \approx 50$ μs. The number of such events was 51 of 124. On the grounds that neutrons are produced by synthesis reactions $^2H(^2H, n)^3He$ in lightning channels, with these time delays and a velocity of the 2.45-MeV neutrons, the total yield of $0.9 \times 10^7 - 2 \times 10^{10}$ neutrons per lightning stroke was estimated. The time delays for the remaining multiple-neutron events were spread between 60 μs and 2×10^5 μs. The inferred neutron yields were so high that the authors consider them to be incompatible with the physical conditions in lightning channels and believe that multi-stroke flashes generated neutrons in these events. The first stroke of the particular flash triggered the recording system, whereas neutrons were produced by subsequent strokes belonging to the same or a different flash. There is a chance that multi-neutron events with anomalous long time delays are due to neutrons that were emitted in directions opposite to the monitor and were detected only after relatively long wandering due to multiple scattering in matter, during which they undergo substantial energy degradation. As a plausible explanation of these events, Shah et al. [77] also mentioned the production of neutrons of lower energies by the reactions $^{12}C(^2H, n)^{13}N$ and $^{14}N(^2H, n)^{15}O$.

To significantly reduce the inevitable interference of neutrons produced by cosmic rays, Shyam and Kaushik searched for thunderstorm neutrons at sea level [78]. A neutron detection system in Mumbai, India, comprising

Table 1. Observations of thunderstorm neutrons.

Observation time	Country, location	Altitude above sea level	Associated with	Number of count rate enhancements	Max count rate excess	Enhancement duration	Max number of detected neutrons	Reference
	RF	Near space						[81]
2008 – 2009	India	Low elevation	Lightning					[78]
31.05.1998	RF, Moscow	Low elevation	Lightning		180 s^{-1}	10 – 20 s		[80]
2008 – 2009	Brazil, São José dos Campos	610 m	Lightning		10^5 m^{-2} min^{-1}	< 2 min		[82]
2009 – 2012	RF, Yakutsk, Siberia	94 m	Lightning	9	2.4×10^3 m^{-2} min^{-1}	3 – 4 min		[83]
May 1980 – May 1983	India, Gulmarg, Himalayas	2743 m	Lightning EMPs	124			87	[77]
May 2006 – October 2009				150		1.28 ms	63	[86]
Since 2003	Armenia, Aragats	3250 m	Thunderstorm	100	56 m^{-2} min^{-1}	10 min	$\approx 5 \times 10^3$	[33]
					53 m^{-2} min^{-1}	4 min	$\approx 4 \times 10^3$	[34]
22.07.2010	China, Tibet	4300 m	Thundercloud	1		40 min		[31]
11.06 – 20.08.2010	Kazakhstan, Tien Shan	3340 m	Lightning	25	3×10^4 m^{-2} min^{-1} *	≈ 1 min		[40]
12.06 – 24.07.2013				39	$\approx 10^6$ m^{-2} min^{-1}	0.2 – 542 ms	500	[41, 42]
05.01.2012	Japan	Coast of Sea of Japan	Thundercloud	1	58 m^{-2} min^{-1}	10 – 20 s		[45]
03.12.2015			Lightning	1		9 ms	1000 cm^{-2}	[106]

* Estimation by the author of the present review: 5×10^5 m^{-2} min^{-1}.

Table 2. Neutron delay time relative to lightning EMP.

Observation period	Total number of neutron events/ total number of registered lightning EMPs	Time delay, μs	Number of neutron events	Maximal number of neutrons in event	Reference
May 1980 – May 1983	124/11200 $n \geqslant 3$	≈ 10 – 200 $\approx 300 - 10^3$ $\approx 10^3 - 10^4$ Vicinity of 10^5	78 4 29 12	87 32 40 33	[77]
May 2006 – October 2009	150/150 $n \geqslant 3$	1 – 300 $6 \times 10^3 - 1.5 \times 10^4$ $4 \times 10^5 - 2.3 \times 10^5$	9 6 5	52 63 19	[86]

16-cylinder boron counters imbedded in a polyethylene moderator, was used. Strong count increases were observed during lightning flashes: 57.5 counts in 100 μs above the fair weather count background of 26.5. Base on the distance to a high chimney with a lightning arrestor at the top located in the monitor vicinity, which attracted lightning bolts, the authors evaluated the maximum number of thunderstorm neutrons by a magnitude of 1.4×10^9 per bolt. The neutrons were assumed to be produced by the same reaction of nuclear synthesis $^2H(^2H, n)^3He$ due to either collective acceleration or the runaway of deuterium ions in lightning channels to the high energies required for the nuclear synthesis to be efficient.

Kuzgevskij [80], also proceeding from the idea that thunderstorm neutrons originate from the nuclear synthesis $^2H(^2H, n)^3He$ in lightning channels, evaluated a number of neutrons in a lightning pulse corona by a magnitude of $10^9 - 10^{10}$ per stroke, which is orders of magnitude lower than the estimate by Libby and Lukens [72], even with the correction by Mosher, cited in the paper [75], but agrees with the estimate by Shyam and Kaushik [78]. The author of [80] reports about events with count rate increases of the Lomonosov Moscow State University neutron counter that were repeatedly observed during thunderstorms. In particular, on May 31, 1998, two enhancement events with a count rate up to about 180 s^{-1} above the background with a duration of $\approx 10 - 20$ s were recorded. The increases comprised a series of shorter bursts.

The authors of paper [81] consider thunderstorms to be responsible for the high neutron fluxes they detected with instruments with effective areas of 30 cm^2 and 100 cm^2 aboard the Kolibri-2000 satellite with an orbit altitude of 350 km. But, though the numbers of neutrons that escape to satellite altitudes from high-altitude photon sources are greater than the numbers reaching the ground level from low-altitude sources, neutron fluence from high-altitude sources is drastically reduced due to spatial dispersion. According to

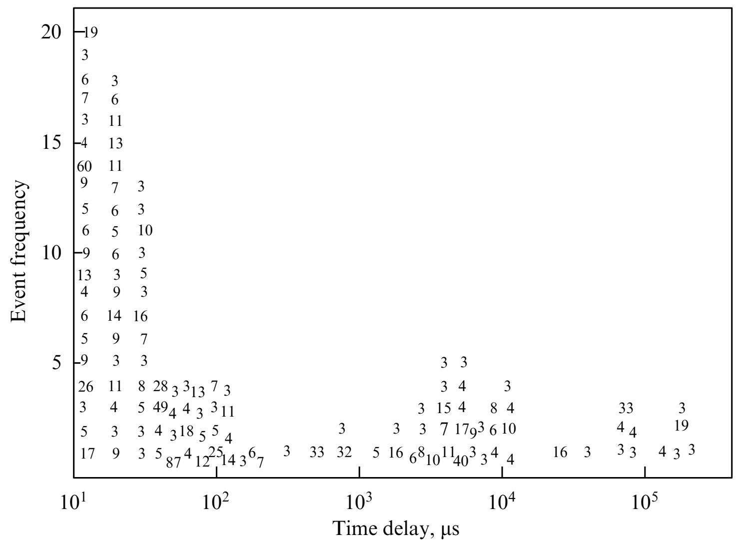

Figure 2. Time delay distributions of 124 lightning-correlated events with three or more neutrons; the digits represent the number of constituent neutrons recorded in the sampling time of 320 μs [77].

the results of numerical simulations carried out by Carlson et al. [87], thunderstorms could not be responsible for the high neutron fluxes reported in paper [81]. Really, based on 10^{12} photonuclear neutrons per TGF computed in [87], from numerical simulations of their transport into near space, the neutron fluence $\Phi_n \approx 10^{-5}$ cm^{-2} at the altitude of 350 km was obtained for the upward directed photon source located at the altitudes 15–20 km at the sub-satellite Kolibri-2000 point, consistent with the data of satellite-based observations of TGFs [88, 89]. Such a Φ_n magnitude is too low to be detected with instruments with the abovementioned effective areas; therefore, in [87], strong doubts are expressed that the responses of the Kolibri-2000 detectors [81] were due to thunderstorm neutrons. Increasing the number of photonuclear neutrons in the source by a few orders of magnitude does not eliminate the concerns.

Martin and Alves [82] observed atmospheric neutrons with a lead- and moderator-free helium tube counter with an effective area of 70 cm^2. The observations were carried out from October 2008, to August 2009 in the city of São José dos Campos, Brazil, at an elevation of 610 m a.s.l. During a thunderstorm on January 9, 2009, a neutron burst was recorded with a count rate of 690 min^{-1}, which is more than 1,000-fold above the mean neutron count rate before the event. The whole event lasted less than two minutes.

Chilingarian's group [33–37] has for a long time been carrying out observations in Armenia of cosmic rays at the Aragats Space Environmental Center (ArSEC) at the altitude of 3,250 m a.s.l. Combined measurements of gamma rays and neutral and charged particles are executed with detectors of the Space Environmental Viewing and Analysis Network (SEVAN) and the Aragats Solar Neutron Telescope (ASNT). Additionally, neutrons are measured with the NM64 Aragats Neutron Monitor (ArNM) comprising 18 boron counters with an effective area of 18 m^2 shielded with a 5-cm lead producer (gamma-ray absorber) and 10-cm-thick polyethylene layer (neutron moderator). The authors emphasize the 18NM64's outstanding feature to be its suppressed sensitivity to leptons. For the first time, simultaneously combined fluxes of high-energy electrons, muons, γ-rays, and neutrons were measured during thunderstorm activity. In particular, nearly 100 events of count rate increases in the numbers of electrons, gamma-rays, and neutrons associated with thunderstorms were detected between 2003 and 2009, including 50 events in 2007–2009 at the solar activity minimum; therefore, these last events, in the authors' opinion, have a thunderstorm origin. For instance, on September 19, 2009, when thunderclouds were at altitudes of 100–200 m above the ArSEC, a large ArNM count rate increase was observed [33]. Lightning discharge accompanied by precipitations occurred a half an hour before this event. A significant ArNM count rate excess that was recorded above the background (maximal excess 56 m^{-2} min^{-1}, with neutron number of $\approx 5 \times 10^3$) lasted 10 min, which is 7 min shorter than the duration of the gamma-ray increase (Fig. 3).

Chilingarian et al. [33] note that the interplanetary magnetic field was very stable on September 19, 2009, such that an extra cosmic ray flux, which could account for the increase in ArNM counts, was absent and, therefore, the peak in the ArNM 1-minute time series proves the detection of neutron flux enhancement in ArNM, in spite of it (5.1σ) not being as significant as the detection of neutral particles by ASNT (63σ) and SEVAN (23σ). High-energy electrons and gamma rays were detected simultaneously with neutrons in this event; the corresponding absolute electron ($3.06 \times 10^5 \exp(-0.18\varepsilon)$) and γ-ray ($8.57 \times 10^6 \varepsilon^{-2.83}$) spectra (particle numbers per m^2 per min) incident on the detectors or the roof of the building where the detectors are located are illustrated in Fig. 4. The spectra were reconstructed using the measured spectra of the energy absorbed by the detectors. The absolute spectra were obtained by multiple solutions to the direct problem using the analytic formulas of the RREA gamma ray spectra (power, exponential, or power with cutoff).

Simultaneously with neutrons, the observation of enhancements in fluxes of electrons and gamma photons with energies above the photonuclear threshold $\varepsilon_{th,N} = 10.55$ MeV in air is considered an unambiguous confirmation of the photonuclear mechanism for neutron production and a demonstration that RREA was developing very closely with ArSEC. To conclusively prove neutron production, the

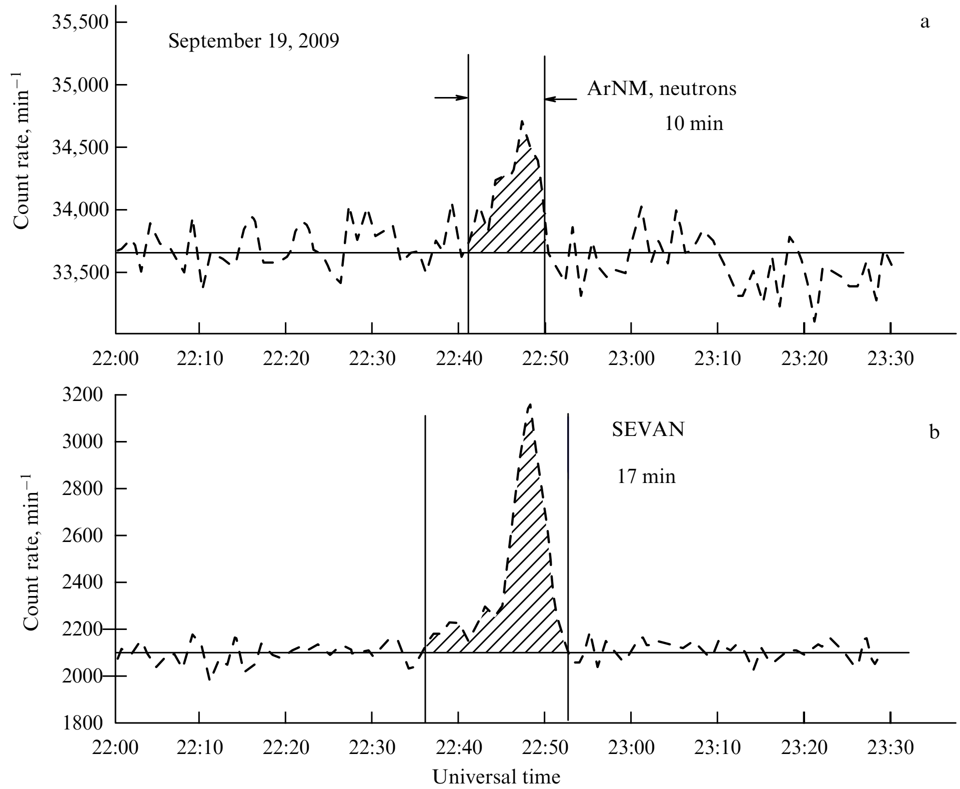

Figure 3. One-minute counts of particles by (a) ArNM and (b) SEVAN detectors at ArSEC; the additional counts in the event on September 19, 2009 are dashed [33].

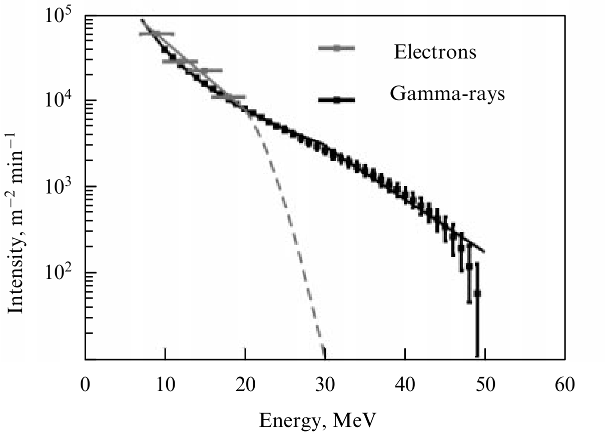

Figure 4. Electron and gamma-ray spectra in the event on September 19, 2009, on ArSEC [33].

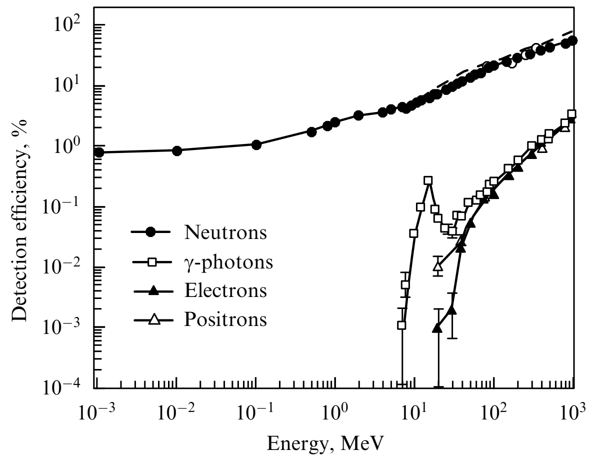

Figure 5. Computed detection efficiencies of NM64 at various radiation levels. Statistical 1σ errors are given [31]. The dashed curve is the NM64 neutron detection efficiency computed by Clem and Dorman [90]. Circles denote the experimental data by Shibata et al. [91] for the neutron detection efficiency.

authors, using a conventional approach in a time series statistical analysis, formed a 3-minute time series summing the counts of the three succeeding minutes after the initial one-minute series. As a result, the significance of the three-minute neutron peak was increased to about 7.8σ. The evaluated chance probability of obtaining the peak in the three-minute time series is negligibly small: 10^{-14}. The final conclusion by the authors of [33] is that the ArNM monitor, in the event on September 19, 2009, detected photonuclear neutrons of a thunderstorm origin, the source of which was located in the atmosphere.

Tsuchiya et al. [31] reported results of observations carried out with a solar neutron telescope (SNT) and YBJ NM neutron monitor installed at the Cosmic Ray Observatory (4,300 m a.s.l.) in Yangbajing, Tibet, China. The YBJ NM comprises 28 NM64-type monitors. Each boron counter comprising the monitor is a tube 190.8 cm in length with a radius of 7.4 cm surrounded by polyethylene plates 7.5 cm thick and lead blocks with an average thickness of 120 g cm^{-2}. Additionally, to decelerate neutrons, each counter constituting the monitor was inserted into a 2-cm-thick polyethylene tube. The YBJ NM area of 32 m^2 is the largest among worldwide neutron monitors. The computed YBJNM detection efficiency of neutrons exceeds by orders of magnitude that of other penetrating radiations: γ rays, electrons, and positrons (Fig. 5).

Table 3. On-ground neutron fluence Φ_n at different detection altitudes h_{det} and altitudes of the parent gamma-ray source h_γ [160].

h_γ, km	h_{det}, km	Neutron fluence, m^{-2}							
		Measured				Computed			
		[77]	[33, 34]	[86]	[40]	[94]	[96]	[87]	[31]
?	2.74	30 – 670		56 – 700					
?	3.25		5×10^4						
15 – 5	0					$(0.03-7) \times 10^2$			
12 – 8	3					$(0.35-4) \times 10^2$			
?	3.34				$(2-3) \times 10^4$				
4 – 2	0						$2 \times (10^3-10^5)$		
5 – 3.5	3						$(0.9-2) \times 10^7$		
5	0							3×10^2	
2.5	0							10^4	
5.2	4.3								1.4×10^4

During the rainy season from May to October 2010, 25 lightning EMP events with fields largely deviated from fair-weather fields were recorded [31]. Five of the events were accompanied by prolonged count rate increases in SNT and YBJ NM. Four of them lasted from 10 to more than 30 min, of which one event, observed on July 22, 2010, lasted about 40 min. They are much longer than the events observed in winter thunderstorms on the coast of the Sea of Japan [28]. The authors of [31] believe that a difference in life cycles of mature stages of winter and summer thunderclouds is a probable reason for this difference. The SNT detected significant γ-ray signals with photon energies above 40 MeV in the event. Such prolonged high-energy events had never been observed earlier in association with thunderclouds or during thunderstorms. They clearly evidence RREAs with electron energies high above 40 MeV being capable of developing in thundercloud fields for 40 min.

Keeping in mind that the high-energy sections of thunderstorm γ-ray spectra detected in near space [39] and at sea level [28] obey a power law with an index of -2.7 [39] (close to 2.83 in paper [33]) and -2 [28], and in view of the theoretical bremsstrahlung γ-ray spectrum is the hardest with the index -1, the authors of [31] executed Monte Carlo simulations of gamma-ray transport, assuming a source with a power-law spectrum in the range from 10 to 300 MeV with three index values: -1, -2, -3. It is known that the conventional spectrum of the RREA bremsstrahlung is exponential, with the characteristic energy of 7 MeV [89, 92, 93]. Possibly, the reason for the disagreement with the observed power-law spectra is that the spectra of RREA electrons and their bremsstrahlung γ rays were computed up to the steady-state spectrum, i.e., unvarying with increasing computation duration, whereas, most likely, there was no sufficient time for the observed spectra to become steady. With a specific number of photonuclear neutrons $N_{nl} = 4.3 \times 10^{-3}$ per gamma photon with the energy above the photonuclear threshold $\varepsilon_{th,N} = 10.55$ MeV [94] for the downward directed γ-ray flux with the source at the altitude of 900 m (5.2 km a.s.l.), which agrees with the typical height of 1 km of cloud bases of summer thunderclouds above the Tibetan Plateau [95], the authors of [31] evaluate a fluence of thunderstorm neutrons arriving at the observatory level in the energy range from 1 keV to 300 MeV by a magnitude of $\Phi_n \approx 1.4 \times 10^4$ m^{-2}, which is within the limits of the previous predictions $(0.03-1.00) \times 10^4$ m^{-2} [87] and 10^3-10^7 m^{-2} [94, 96] for various source and detector altitudes (cf. Table 3). From this, the authors conclude that "...photonuclear reactions certainly occur during mature stages of thunderclouds" [31].

In papers by a group from the Shafer Institute of Cosmophysical Research and Aeronomy of the Siberian Branch of the Russian Academy of Sciences [83–85], results are communicated of observations of thunderstorm neutrons at an elevation of 100 m a.s.l. in the Tuymaada Valley near the city of Yakutsk, Siberia. The observation site is equipped with a 24NM64 boron monitor embedded in a polyethylene moderator and lead producer. Allowing for the fact that the monitor sensitivity strongly decreases with the neutron energy decrease, such that it is the highest above 10 MeV (sensitivity magnitudes of $<3\%$ for 3 MeV, 2% for 0.5 MeV, and 0.5% for thermal neutrons are presented) (cf. the data in Fig. 5 [31]), the authors of [83] assume that 10 MeV is the lowest energy of efficiently detected neutrons, which significantly exceeds the mean energy of photonuclear neutrons of 3.9 MeV that Carlson et al. [87] predicted. When thunderclouds pass over the observation site, strong on-ground variations in the electric field 1–3 km below the thundercloud bases were recorded for 1–2 hours with strength amplitudes up to 20 kV m^{-1}, which is high above the background of the average field in that region of 100 V m^{-1}. In the range of 10 km around the observation site, 30 thunderstorms were registered during the observation period from 2009 to 2012. Neutron fluxes of 2.4×10^3 m^{-2} min^{-1} lasting 3–4 min were observed during the most severe 9 thunderstorms with negative lightning discharges during events when the electric field strength on the ground exceeded a magnitude of -16 kV m^{-1}, which in the opinion of the authors of [83–85] is the threshold for thunderstorm neutron production.

A collaboration of seven scientific organizations of Kazakhstan and Russia executed at the Tien Shan Mountain Cosmic Ray Station (3,340 m a.s.l.) during thunderstorm activities in the summer of 2013 measurements of penetrating radiations in the X-ray and γ-ray ranges (energies from >30 keV to >300 keV) coincident with neutron bursts [41, 42]. The neutrons were measured in the thermal energy range

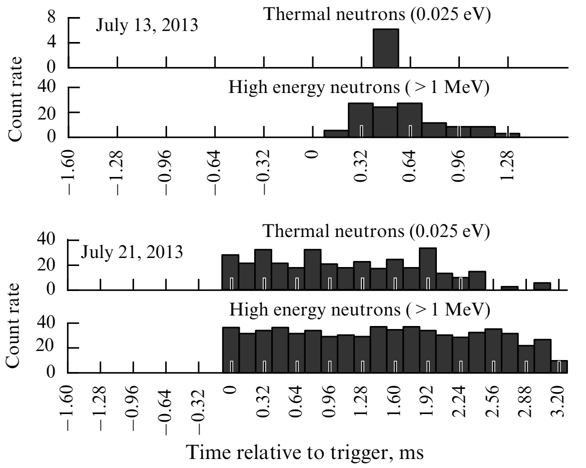

Figure 6. Neutron signals (pulse number in 160 μs) registered on July 13 and 21, 2013 at the Tien Shan Mountain Cosmic Ray Station in events with a close lightning bolt stretched around the moment of the lightning trigger [41, 42].

($\approx$ 0.025 eV) with proportional helium counters and in the range of $\geqslant$ 1 MeV with an 18NM64 monitor, in which boron counters were enveloped with a 10-cm-thick lead tube (gamma-ray absorber) and a polyethylene moderator of neutrons. The emissions were observed to correlate with the onset of the lightning initiation [42].

For instance, in the event on July 13, 2013, the count of thermal neutrons with helium counters was delayed 0.4 ms relative to the discharge start; the delay of the counts of high-energy neutrons with the monitor was 0.08 ms; in the event on July 21, 2013, the count in both ranges started 0.08 ms ahead of the discharge start (Fig. 6). Forty events of count rate increases were detected by helium counters, with the maximal number of 47 of neutrons counted in 200 μs in one of the events [41]. Magnitudes of the lightning-correlated neutron intensity of about 2×10^5 m^{-2} s^{-1} and about 10^6 m^{-2} s^{-1} measured on July 13, 2013 and on July 21, 2013, respectively, greatly exceed those at quiet time: 1.5×10^2 m^{-2} s^{-1} and 3×10^2 m^{-2} s^{-1}, respectively. The measured gamma spectra in both events decrease almost exponentially from about 10^6 m^{-2} s^{-1} at 30 keV to about 6×10^5 m^{-2} s^{-1} at 600 keV, which "...1.5–2 orders of the magnitude exceed the mean values monitored without binding to the lightning trigger" [42].

Paper [41] describes a time structure of neutron count rate enhancements correlated with lightning EMPs (Fig. 6). The duration of the increases varied in very wide ranges: from 0.2 to 180 ms (helium counters) and from 1 to 542 ms (the monitor). Neutrons were emitted mainly in 200–400 μs bursts. Remarkably, both gamma and electron TGFs, whose durations are in the millisecond range, also consist of shorter bursts $\approx$ 100 μs in duration (e.g., [7, 20, 23, 24, 39]). The total yield of thunderstorm neutrons was estimated at a magnitude of $\approx 10^{10}$ per lightning discharge [42]. The authors consider the measured count rates to be too high to be explained by "...neutron production by photo- and electronuclear reactions inside the electron–photon avalanche in the atmosphere..." [42] and show by Monte Carlo simulations that neutrons were mainly produced in the environmental dense medium (soil) around the detectors. This possibility was missed in papers [34, 96–101], where the analysis was executed assuming that thunderstorm neutrons are generated in air or directly in the detectors.

Many years after the experiment by Shah's group [77], it was repeated by the Ishtiaq's group [86] with an upgraded LFGNM. During the observation period, 150 EMPs of lightning discharges were recorded (see Table 2). Correlated with each of them were events with more than two observed neutrons. For instance, in May and June of the year 2006, major thunderstorm activities occurred in the vicinity of the LFGNM, which was triggered 60 times by the lightning EMPs. Out of these triggerings, in 50 events more than 4 neutrons per event were recorded (in paper [86], observation data for only 20 of these events are available, as shown in Table 2).

Table 2 presents the total number of the events with three or more neutrons correlated with lightning EMPs, the total number of registered EMPs, delay times, defined as the time lag between the monitor triggering and counting of the first neutron, the detected number of EMP-related neutron events, and the maximal number of neutrons in the event [77, 86]. Remarkably, the neutrons are distributed in three groups according to the delay time, which are rather close in both observations. The numbers of neutron events decrease as the delay time increases. Possibly, this is evidence that sources of such events were correspondingly distant from the monitor and, as a consequence, the neutron flux was correspondingly attenuated: as a result, smaller numbers of neutrons from distant sources reached the monitor. The decrease is especially pronounced in the observations by Shah et al. [77], where the maximal number of neutrons in the event also decreases with a delay time increase. This might also be the case in the observations by Ishtiaq et al. [86] provided that all 150 events are taken into account.

2.2 Registration by scintillation detectors

The coast of the Sea of Japan is an ideal place for on-ground observations of thunderstorm high-energy emissions [28, 30, 102] in view of the fact that the charge centers of the coastal winter thunderclouds are very low [103]. Based on the gamma radiation spectrum registered by Tsuchija et al. [28], which is extended high above the threshold of photonuclear reactions in air $\varepsilon_{\rm th,N} = 10.55$ MeV, numerical simulations predict neutron generation by thunderstorms on the coast of the Sea of Japan and the possibility to observe it [96].

Kuroda et al. [45], using a prototype of the anti-neutrino detector PANDA (antiProton ANihilation at DArmstadt) comprising 36 stacked $10 \times 10 \times 100$-cm bar scintillation modules with a coating containing gadolinium with a density 4.9 mg cm^{-2} disposed at the Ohi Power Station on the coast of the Sea of Japan, observed in December 2011 and January 2012 three γ-ray bursts related to winter thunderclouds. The radiation entered the detector from the direction close to the zenith with a maximum count rate of (550 ± 10) s^{-1} in the energy range above 3 MeV with the spectrum extending up to 15 MeV. The neutrons were observed synchronously with the third gamma-ray burst detected on January 5, 2012 [45]. To select the neutrons with high confidence, the delayed coincidence technique was used. A high-energy neutron entering the detector transferred part of its energy to the recoil-proton in the plastic (prompt event). Then, after multiple scatterings, the neutron was eventually captured by the gadolinium nucleus; as a result of the de-excitation, a γ-cascade was emitted with a total energy of 7.9 MeV from ^{157}Gd and 8.5 MeV from ^{155}Gd (the delayed event), which was

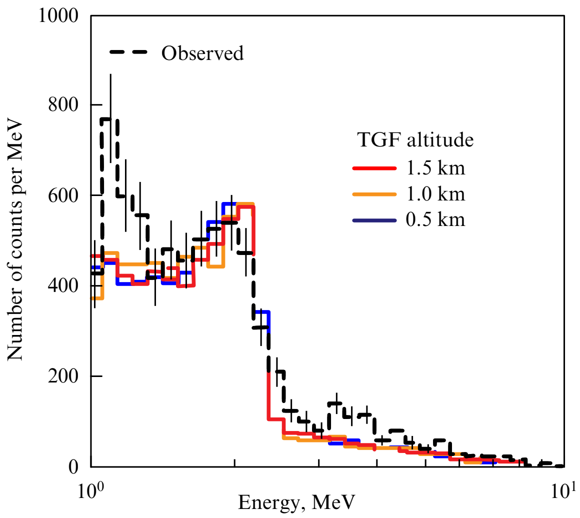

Figure 7. (Color online.) Comparison of on-ground gamma-ray spectra: measured and computed for three altitudes of the radiation source [106]. The computed spectra for all assumed TGF attitudes are very close; the line with the photon energy of 2.223 MeV is clearly seen in both measured and calculated spectra.

recorded. With the use of these data, a maximum rate of neutron production $(14 \pm 5)\ \text{s}^{-1}$ per unit of the detector area ($\approx 58\ \text{m}^{-2}\ \text{min}^{-1}$ in Table 1) was estimated. Kuroda et al. [45] noted that "...the observation of fast neutrons on the ground implies that more neutrons are produced in the air between a thundercloud and the ground and even in the cloud itself. Those neutrons, however, would not reach the ground because of the short absorption length in the air."

According to results of Monte Carlo simulations Kuroda et al. carried out in RREA terms [55], the observed gamma spectra are well described by the bremsstrahlung of electrons with plateau-like energy distributions in the range of 14–20 MeV propagating downwards from an altitude of 100 m. But the energy distribution of RREA electrons at high energies is exponential, independent of the electric field strength and air density [33, 104, 105], as illustrated, for instance, in Fig. 7 of paper [104], where steady-state (i.e., unvarying with increasing computation duration) electron distributions calculated by the Monte Carlo technique for two strongly different magnitudes of the field overvoltage $\delta = eE/(F_{\min}P)$ relative to the minimum of the electron drag force in air ($F_{\min} = 218$ keV m^{-1} atm^{-1}) (see Fig. 1) are presented.

For observations of high-energy thunderstorm emissions, a collaboration of seven institutions from Japan and the USA [106] used an instrument consisting of three cylindrical scintillation detectors with equal length and diameter: BC-408 (plastic), BC-408 (plastic), and NaI(Tl) (crystal) with sizes of 2.5 cm, 12.5 cm, and 12.5 cm, respectively. In December 2015, the instrument was deployed in the coastal area of the Sea of Japan about 300 m from a lightning protection tower. During a thunderstorm on December 3, 2015, the tower was struck by lightning initiated by a positive upward leader. All three detectors recorded a sharp burst of 9-ms-long counts coincident with a large negative change in the atmospheric electric field. For analysis, the readings of the BC-408 with sizes of 12.5 cm, capable of recording energies in the range of 0.3–25 MeV, were used. Bowers et al., the authors of paper [106], consider counts of this detector clustering in the vicinity of 2 MeV (see Fig. 7) to be a signature of primary neutrons and believe that the emission of photons with the energy of 2.223 MeV as a result of the radiative capture of neutrons $\text{H}_1^1(\text{n},\gamma)\text{H}_2^1$ by hydrogen nuclei (protons), the main constituent of the scintillator, causes the count clustering.

To analyze the observation results, Bowers et al., based on the likely range of altitudes of a localization of the main negative charge center in Japanese winter thunderclouds, simulated a downward TGF from altitudes of 0.5 km, 1.0 km, and 1.5 km. Earlier [96], numerical simulations demonstrated that a gamma radiation source at such altitudes best of all fits the gamma spectrum registered on the coast of the Sea of Japan in the work by Tsuchiya et al. [28]. Bowers et al. simulated their experiment using the conventional TGF spectrum $\varepsilon_\gamma^{-1}\exp(\varepsilon_\gamma/6.6\ \text{MeV})$ [18] in the range of photon energies ε_γ up to 40 MeV. Trajectories of all neutrons, both those produced through photonuclear reactions and their secondaries, were tracked down to the ground and into the instrument. The observed and simulated spectra are compared in Fig. 7. An agreement between the observed and simulated 2.223-MeV line is obvious. For the TGF from the altitude of 1.0 km, the count rate observed in [106] from photonuclear neutrons is consistent with the typical TGF brightness of $\sim 10^{17}$ gamma photons [107]. The authors calculated the on-ground gamma fluence to be $\sim 10^5\ \text{cm}^{-2}$, "...much larger than the total combined fluence of all TGFs observed by satellites since 1994" [106], and an evaluation of the total number of photonuclear neutrons produced for this event, $\sim 10^{12}-10^{13}$, is consistent with results of the previous simulations [87, 108].

Bowers et al. note in [106] that large BF_3 and ^3He proportional counters used in previous observations of thunderstorm neutrons, discussed in the Section 2.1, which are believed to be sensitive only to thermal neutrons, are actually susceptible to contamination from high-energy electrons and gamma-photons, as has been shown in papers [31, 98, 99]. They emphasize that using small detectors allows observing unique spectral and temporal photo-neutron gamma signatures of photonuclear neutrons and, following the authors of paper [42], emphasize that "...ground thermalization is important when considering the instrument response and effective radiation dose from neutron flashes."

3. Elementary process responsible for the production of thunderstorm neutrons

3.1 Processes involving high-energy electrons and their bremsstrahlung

In the first papers reporting observations of thunderstorm neutrons correlated with lightning discharges [76–78, 80], as in the paper by Libby and Lukens [72], the neutron production was believed to be connected with the reaction of nuclear synthesis $^2\text{H}(^2\text{H},\text{n})^3\text{He}$ in lightning channels, despite the skeptical attitude of Fleisher et al. [75] to the possibility of this reaction occurring in lightning plasmas, based on the scaling of the data of neutron-producing laboratory discharges (cf. Introduction).

In papers [97, 100], fundamental interactions that would be capable of accounting for thunderstorm neutrons production are analyzed in the framework of the RREA conception, though in the high energy range characteristic times of strong, electromagnetic, and weak interactions are related as $\tau_{\text{str}}:\tau_{\text{el}}:\tau_{\text{weak}} \sim 10^{-14}:10^{-11}:1$, such that, at first glance, it

Table 4. Data of observations of short thunderstorm gamma-ray flashes and prolonged gamma glows.

Reference	[13, 49]	[28]	[29]	[30]	[31]	[38]	[20]	[23, 24]	[39]	[46]	[45]	[33]
Max ε_γ, MeV	> 10	70	10		> 40	10	20 – 40	30 – 38	100	⩾ 10.5 *	> 17	40 – 50
Duration	> 2 min	40 s	> 1 min	90 s	40 min	20 min	0.2 – 3.5 ms	0.5 – 1 ms	0.5 – 1 ms	< 1 ms	1 – 3 min	Tens of min
Relation to lightning	Association with lightning	Before lightning					Association with lightning					Before lightning
Location	North Caucasus	Coast of Sea of Japan		Gifu	Tibet	Fuji	Near space			Coast of Sea of Japan		Aragats
Country	Russia	Japan			China	Japan	USA		Italy	Japan		Armenia
Altitude a.s.l. or satellite orbit, m	1,700	30 – 40		2,770	4,300	3,776	RHESSI 600,000	Fermi 560,000	AGILE	30 – 40	Sea level	3,250

* i.e., above the photonuclear threshold, because neutrons were generated, judging by the e^+e^- annihilation line.

seems that the strong interaction dominates. Considered are reactions of nuclear synthesis, photonuclear reactions, electron-induced reactions (electro-disintegration ${}^{n}_{m}A(e^-, n)^{n-1}_{m}A$ and opposite to the β-decay reaction $e^-(p^+, n)\nu_e$ [109]), of which the latter were not taken into account earlier [79, 98, 101, 110–112], in spite of the fact that the hard gamma-ray flashes observed in correlation with thunderstorms are merely secondary bremsstrahlung of high-energy electrons whose flux, obviously, is more intensive than that of gamma-rays. It is shown that photonuclear reactions dominate as thunderstorm neutron producers. In contrast to the zero yield of nuclear synthesis, the expected neutron yield of electro-disintegration reactions in thunderstorm atmospheres is significant, though it is much smaller than the yield of photonuclear reactions. Estimates executed with the use of the cross section of the reaction $e^-(p^+, n)\nu_e$ derived by Srivastava et al. [109], demonstrate insignificant neutron yield in the $e^-(p^+, n)\nu_e$ reaction.

Thus, neutron flux increases in thunderstorm atmospheres are caused by photonuclear and, to a lesser degree, by electro-disintegration reactions as a result of RREAs developing in extended fields of thunderclouds and localized fields of lightning discharges [41, 42, 79, 94, 96–100, 110–113]. The high-energy electrons constituting the RREA, while multiplying and interacting with atomic particles in atmosphere, radiate bremsstrahlung in the X-ray and γ-ray ranges. As cited in the Introduction, beginning in the early 1980s, these radiations have been rather frequently registered on Earth's surface, aboard aircraft, from balloons, and in near space aboard artificial satellites of Earth. Measured spectra of thunderstorm gamma radiation are stretched up to photon energies ε_γ (cf. Table 4) corresponding to thundercloud voltages and exceeding the thresholds of photonuclear reactions with the main components of atmosphere and the solid surface of Earth: $\varepsilon_{\mathrm{th,N}}(\gamma, n) \approx 10.55$ MeV, $\varepsilon_{\mathrm{th,O}}(\gamma, n) \approx 15.7$ MeV, $\varepsilon_{\mathrm{th,Ar}}(\gamma, n) \approx 9$ MeV, $\varepsilon_{\mathrm{th,Si}}(\gamma, n) \approx 10$ MeV, $\varepsilon_{\mathrm{th,Al}}(\gamma, n) \approx 8.5$ MeV, $\varepsilon_{\mathrm{th,Fe}}(\gamma, n) \approx 10$ MeV. Exactly the high-energy electrons and γ photons of secondary bremsstrahlung are capable of knocking out neutrons from atmospheric nuclei (${}^{14}N, {}^{16}O, {}^{40}Ar$), solid matter around the detectors (${}^{27}Si, {}^{26}Al, {}^{56}Fe, {}^{16}O$), and the detectors themselves.

In this sense, very representative are data on the TGF timing and spectral parameters (cf. Table 4) Tavani et al. [39] obtained from observations aboard the Italian Space Agency satellite AGILE (Italian: Astro-revilatore Gamma and ImmaginiLEgerro) equipped with a mini-calorimeter

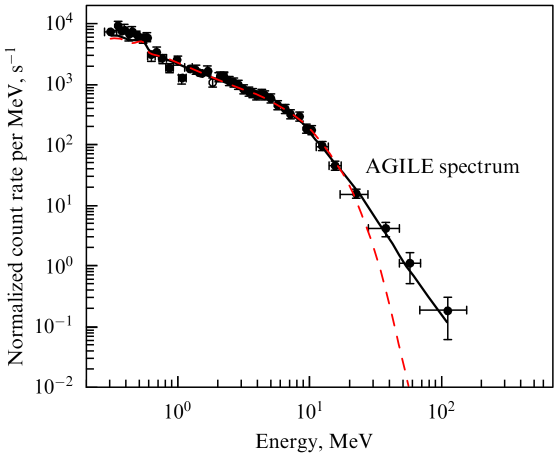

Figure 8. (Color online.) Background-subtracted combined spectral count rate of the 130 TGFs detected aboard the AGILE satellite. The solid curve is a fit with functions $f(\varepsilon) \sim \varepsilon^{-(0.5\pm0.1)}$ in the energy range of 1 MeV $< \varepsilon < \varepsilon_c$ and $f(\varepsilon) \sim \varepsilon^{-(2.7\pm0.1)}$ in the range $\varepsilon_c < \varepsilon < 100$ MeV with $\varepsilon_c = (7.5 \pm 0.5)$ MeV; the dashed curve is a pre-AGILE [20, 21, 89, 146] phenomenological model $f(\varepsilon) \sim \varepsilon^{-\alpha}\exp(-\varepsilon/\varepsilon_c)$ with $\alpha = 0.4 \pm 0.2$ and $\varepsilon_c = (6.6 \pm 1.2)$ MeV [39].

(MCAL) capable of detecting pulsed events in the energy range from 0.350 to 100 MeV [39]. Figure 8 illustrates the background-subtracted cumulative energy spectrum of the 130 TGFs observed from June 2008 to January 2010. It extends up to 100 MeV and obeys a power law above 10 MeV; in this, it does not reconcile with RREA models predicting exponential attenuation at high energies. This power-law gamma spectrum $\sim \varepsilon^{-(2.7\pm0.1)}$ in the range above ≈ 7.5 MeV is very close to the spectrum of prolonged gamma glows $\sim \varepsilon^{-2.83}$ observed at Aragats at the elevation of 3,250 m (cf. Table 4) [33].

Such a gamma spectrum strongly supports the photonuclear origin of thunderstorm neutrons, because it extends not only high above the thresholds of neutron-producing photonuclear reactions in nitrogen and oxygen but also high above the positions 23.3 MeV (${}^{14}N$) and 22.7 MeV (${}^{16}O$) of the maxima of the cross sections of these reactions. The authors of paper [39] conclude that "...the high-energy tail above 10 MeV turns out to be not a small fraction (close to 1% as considered, e.g., in Ref. [87]), but rather amounts to about 10% of the total energy" and predict a typical neutron yield $N_n \geqslant 10^{13}$ per TGF, which is an order of magnitude larger than the neutron yield 10^{12} predicted in [87] on the basis of results of numerical simulations of gamma-ray transport, and is closer to other predictions: the first estimates of 10^{15} for gigantic stratospheric discharge [79, 110, 111] and 4×10^{13} for intracloud lightning discharge [111]; magnitudes $1.6 \times 10^{14} - 1.1 \times 10^{15}$ obtained from numerical simulations of high-altitude discharge and its emissions [108]; a lower bound of $\geqslant 4 \times 10^{12}$ [94] on the neutron number computed using the RREA bremsstrahlung rate [92] and a constraint on the domain of gamma-ray generation [108] using the specific number of photonuclear neutrons $N_{\rm nl} = 4.3 \times 10^{-3}$ produced per gamma photon with the energy above the photonuclear threshold $\varepsilon_{\rm th, N} = 10.55$ MeV [94].

Note that primary gamma-ray fluxes in their sources are more intensive and γ-photon energies ε_γ are higher than on detectors. Therefore, the generation of neutrons during gamma-ray transport in the atmosphere, the solid matter around the detectors, and in the detectors themselves is more efficient than it is possible to predict on the basis of the measured γ-photon numbers and energies. Even if the γ-ray sources are inside the lightning channels, the ranges of γ-photons with energies above the thresholds of photonuclear reactions exceed the cross-sectional sizes of lightning channels, such that neutrons are generated outside their volume. The duration of the detected gamma-pulse often greatly exceeds the duration of lightning discharges, reaching tens of seconds and minutes; moreover, the γ radiation frequently terminates prior to the discharge [6, 28–32]. The gamma pulses may only correlate with lightning EMPs; rather frequently, they occur in advance or even do not correlate with them.

Thus, prolonged gamma glows (up to 40 min) capable of producing neutrons were observed in advance of the EMPs [28–31, 38] and, hence, were not produced by lightning discharges. The TGFs registered aboard the RHESSI [20] (Reuven Ramaty High Energy Solar Spectroscopic Imager) and Fermi [23] satellites occurred before, simultaneously with, and after the lightning discharges (cf., e.g., [14, 23, 24]). The TGFs detected aboard RHESSI, usually less than 1 ms in duration, occurred within $-3/+1$ ms of the lightning EMPs [14, 15]. It seems that lightning EMPs only triggered the recording electronics, and, if this is the case, the lightning discharges have nothing in common with the production of neutrons and parent to them high-energy electrons and gamma rays as in the observations by McCarthy and Parks [6], in which prolonged X-ray emission detected aboard an aircraft was abruptly terminated coincident with the lightning discharge and, hence, most likely, originated from electrons energized in the large-scale thundercloud field which was switched off by the lightning discharge.

3.2 Nuclear fusion?

Though the photonuclear origin of thunderstorm neutrons is now conventional [31, 34–37, 41, 42, 46, 87, 94, 96–101, 110–113], sometimes doubts are expressed [40] and attempts are being undertaken to relate the observed events of neutron flux amplification in thunderstorm atmospheres to nuclear synthesis in lightning channels [86, 114, 115]. This is not surprising: since nuclear reactions are quite common in laboratory discharges, it seems that they can all the more occur in such a grandiose discharge as lightning.

Thus, the authors of paper [40] believe that the 'extraordinary high flux' of thunderstorm neutrons of thermal energies they detected in high-mountain settings "...constitutes a serious difficulty for the photonuclear model of neutron generation in thunderstorm" and noted that paper [33] is the only one in which thunderstorm γ photons with energy $\varepsilon_\gamma = 10-30$ MeV, i.e., above the photonuclear threshold $\varepsilon_{\rm th, N} = 10.55$ MeV, were observed on the ground, but it contradicts the data in Table 4.

Later, in order to interpret results of new observations [41, 42], in which, neutrons in the megaelectronvolt range were detected along with thermal ones, Monte Carlo simulations were carried out in the framework of the photonuclear and electro-disintegration mechanisms of thunderstorm neutrons [42]. Following the assumption by Shyam and Kaushik that the runaway of deuterium ions in lightning channels could account for the neutron flux increases they detected [78], Fülöp and Landreman, to substantiate the observation results in [40] by nuclear synthesis in the lightning channel, developed a very interesting mechanism based on the deuterium runaway in strong electric fields supposedly appearing in lightning plasma due to a violation of plasma quasi-neutrality [114], which, most likely, is impossible, in particular, due to high electron mobility preventing the quasi-neutrality violation [97, 100].

Paiva and co-authors [115] discuss a mechanism opposite to thunderstorm neutron production by high-energy γ photons, namely, they consider the possibility that neutrons produced by reactions of nuclear synthesis ^{2}H(^{2}H, n)^{3}He and ^{2}H(^{4}H, n)^{4}He in lightning channels are responsible for the gamma-ray bursts observed on Earth's surface. The title of paper [86], "Observation of 2.45 MeV neutrons correlated with ... lightning discharges...," straightforwardly points out that the generation of thunderstorm neutrons is connected with the "...fusion reaction ^{2}H(^{2}H, n)^{3}He as one of the possible mechanisms of the neutron generation correlated with lightning." This conclusion is drawn warily based on a single event with the delay time of 14 μs relative to the EMP of lightning striking a tree 300 m away from an LFGNM monitor; given these magnitudes, the energy of the detected neutrons is evaluated at a magnitude of ≈ 2.45 MeV. It is noteworthy, however, that the mean energy of photonuclear neutrons, 3.9 MeV according to the computation by Carlson et al. [87], insignificantly exceeds this magnitude and also fits the distance of 300 m, especially in view of the fact that the velocity is a square root of the energy. Tsuchiya, while analyzing the anomalous count rate of thermal neutrons registered with a helium counter, as reported in paper [40], does not rule out the possibility that the ^{2}H(^{2}H, n)^{3}He reaction contributes to the enhanced count rates either [101].

It would be easy to check directly whether thunderstorm neutrons are produced by nuclear synthesis or by photonuclear reactions, provided that the locus of the neutron source and delay time of the first neutron arrival at the detector are known. However, it is not a simple task to localize the neutron source by direct observations, even when the source locus seems to be absolutely obvious. So, Shah and co-authors [77] also mentioned an event when lightning struck a tree at a distance of 1.5 km from an LFGNM monitor. The result was a 10-neutron event with a time delay of 30 μs (see Fig. 2). The distance calculated for 2.45-MeV neutrons turns out to be one half the actual distance to the tree, from which one may infer a higher neutron energy. However, the authors assume as the most plausible explanation that the first detected neutron in this event was of cosmic-ray origin and the subsequent 9 neutrons were produced by lightning and detected after some time lag.

One more case was observed when a tree, 400 m from the monitor, was damaged by lightning; in this event, 33 neutrons were detected (see Fig. 2). The distance is compatible with the recorded time delay of this event, 71.74 ms, provided that the neutron energy was as low as 0.2 eV. The distance calculated for neutrons with an energy of 2.45 MeV places the tree several orders of magnitude further than the actual distance [77].

In order to once more emphasize the inconsistency of nuclear synthesis as a process supposedly responsible for neutron production in the plasma of a lightning discharge, a result of the analyses executed in papers [97, 100] is presented below. Three neutron-producing reactions of nuclear synthesis are possible in air, namely, $^2H(^2H, n)^3He$, $^{12}C(^2H, n)^{13}N$, and $^{14}N(^2H, n)^{15}O$. From a compilation [116] of published energy dependences of the cross sections of these reactions, it follows that in the low-energy range accessible to deuterons in dense air due to limitations imposed by the charge transfer reactions $D^+ + N_2 \rightarrow D + N_2^+$, i.e., $\ll 1$ MeV, the $^2H(^2H, n)^3He$ reaction dominates. Nevertheless, in view of the high nitrogen concentration in atmosphere, exceeding the deuterium concentration by many orders of magnitude, the contribution of the $^{14}N(^2H, n)^{15}O$ reaction is evaluated. The $^{12}C(^2H, n)^{13}N$ reaction is omitted in view of too low a carbon concentration in air and too small a cross section in the energy range of interest.

As neither the field strength nor plasma parameters in lightning channels during neutron generation are known a priori, the electric field strength reduced to the pressure E/P required to produce at least one neutron by nuclear synthesis reactions in a lightning channel is evaluated [97, 100]. The estimations were executed assuming full dissociation and ionization of the deuterium molecules in the lightning channel with the use of recognized, more or less real, literature data on the magnitudes of the water and deuterium concentrations in atmosphere and channel sizes and duration of the lightning return stroke [117–119]. The synthesis rate was estimated from above for the maximum cross section of the $^2H(^2H, n)^3He$ reaction. For the $^{14}N(^2H, n)^{15}O$ reaction cross section, the extrapolation [116] of the compiled cross sections in the range of low energies was used. For the cross section of the charge transfer reaction $D^+ + N_2 \rightarrow D + N_2^+$, the data from Ref. [120] were used. Even with the magnitudes of the quantities strongly underestimating E/P, it appears that, to produce only one neutron, an extremely strong field is required with $E/P > (55-174)$ MV m^{-1} atm^{-1} for $^2H(^2H, n)^3He$ and $E/P > (44-152)$ MV m^{-1} atm^{-1} for $^{14}N(^2H, n)^{15}O$. These magnitudes significantly exceed not only the self-breakdown reduced field strength in the open atmosphere $(E/P)_{br} \approx 3$ MV m^{-1} atm^{-1} (cf., e.g., [58, 59, 117] and citations therein), but even the E/P magnitudes, which are produced in air gaps of the centimeter range at atmospheric pressure with the use of unique high-voltage pulses with a rise-time in the picosecond range and amplitudes in the range of hundreds of kV, making it possible to avoid the breakdown and early collapse of the voltage such that intensive beams of high-energy electrons are generated (cf., e.g., [1, 2, 69, 121–126] and citations therein).

The above E/P magnitudes, while already strongly overestimated, are increased even more if the registered neutron numbers, and furthermore the neutron number in a source, are used. Being very conservative relative to all parameters of the plasma and sizes of the lightning channels, the above E/P estimation, executed under assumptions extremely favorable for reactions of nuclear synthesis to occur, demonstrates that the charge transfer reactions limit the energy of deuterons in lightning plasmas to too small a magnitude, such that nuclear synthesis as a result of ion heating by an electric field in lightning channels is absolutely impossible in relatively slow lightning discharges in such a dense medium as the lower atmosphere. This is especially true in view of other interactions of deuterium ions being omitted, ionizing impacts and elastic scattering, first of all.

3.3 Observations of neutron production in laboratory discharges in the open atmosphere

Nanosecond discharges developing in air gaps in the centimeter range in a mode of intensive generation of runaway electrons under conditions of multiple overvoltages relative to the self-breakdown voltage [1, 2, 69, 121–126] by their space-time characteristics and magnitudes of the field strength, exceeding many-fold the self-breakdown field strength of ≈ 3 MV m^{-1} atm^{-1}, by no means resemble lightning discharges. Much closer to lightning discharges are long spark discharges developing in the open atmosphere under the action of megavolt high-voltage pulses with durations in the microsecond range. Just as in lightning leaders (e.g., [127]), short-term X-ray flashes have been observed in such discharges [128–137]. X-ray generation under the conditions of these experiments is unexpected, as the maximum of the energy losses of electrons $F_{max} \approx 27$ MeV m^{-1} atm^{-1} (see Fig. 1) exceeds by ten-fold the mean electric field strength in the gas-discharge gaps, but is quite explainable by the acceleration of electrons in the field, locally strengthened in the streamer heads [131–137] or inside the streamer channels where the gas concentration decreases owing to heating [69, 138].

More intriguing are reports about neutron generation in experiments with long (≈ 1 m) spark discharges in the open atmosphere with the use of high-voltage pulses with a duration of ≈ 100 ns and amplitudes of ≈ 1 MV [139, 140]. The neutrons were observed both time-coincident with X-ray pulses, as illustrated in Fig. 9, and with some time delay. As the energy of electrons and, consequently, of their bremsstrahlung photons could not exceed 1 MeV, i.e., was much lower than the threshold of photonuclear reactions in air, nuclear synthesis remains the only conceivable elementary process capable of accounting for the neutron generation. Though from the comprehensive analysis of the experimental data executed in the paper [116] in the framework of the configuration of the experiments in Ref. [139] it was concluded that neutron generation was impossible under the conditions in these experiments, their results remain intriguing, considering a variety of techniques and high level of the executed measurements; therefore, mechanisms unconventional for a dense gaseous medium and elementary processes possibly capable of accounting for the enhanced nuclear synthesis are noted [116]:

• It is expected that in the low-energy range the synthesis of nuclei shielded by electron shells can be more efficient than the synthesis of bare nuclei owing to a Coulomb barrier decrease (see, e.g., [141] and references therein). However, the required increase in the synthesis cross section (by many orders of magnitude) in the low-energy range has not been observed to date.

• Possibly, the $^{14}N(^2H, n)^{15}O$ cross section decreases to low energies not as fast as the extrapolation used in paper

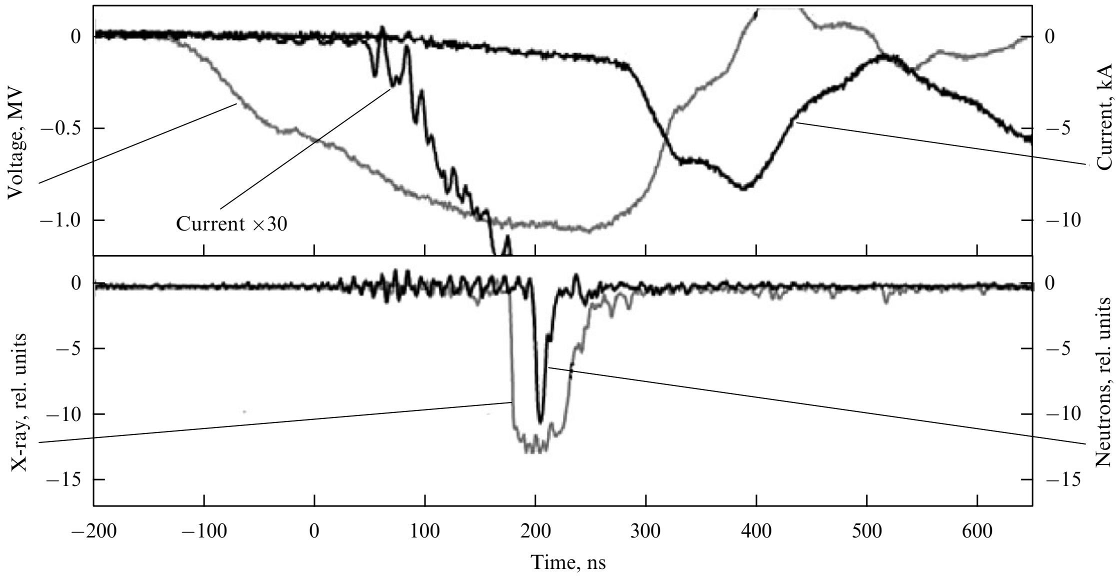

Figure 9. Oscilloscope traces of voltage, current, X-ray, and neutron pulses [139].

[116]. It is unlikely, however, that the synthesis cross sections in the low-energy range increase by many orders of magnitude, as required to overcome the charge transfer.

• 'Cold synthesis' [142], which does not require high energies, is mentioned. It is unclear, however, if it is possible under uncontrolled conditions of ordinary gas discharges, as in Refs [139, 140], especially in view of the extremely short (100 ns) duration of the gas-discharge process.

• As Shyam and Kaushik assumed, some kind of collective acceleration of deuterons could be a cause of the neutron flux increases they detected in correlation with lightning [78]. This may be the acceleration of deuterons captured by an electron flow as observed in laboratory beam plasmas (e.g., [143] and references therein). Though the same limitation remains imposed by charge transfer reactions in a dense atmosphere, it is possible to suggest that collective acceleration is responsible for some portion of the neutron flux increases in plasmas of lightning discharges. This assumption is not absolutely groundless provided that the neutron production in laboratory discharges in the open atmosphere is trustworthy and will be proven in new experiments.

4. Difficulty of interpreting observational data on thunderstorm neutrons

The photonuclear origin of thunderstorm neutrons is proven by numerical simulations [31, 33–35, 41, 42, 87, 94, 96, 112, 113], but direct observational evidence of neutron-producing nuclear reactions during thunderstorms was absent for a long time. It is not difficult to detect neutrons provided that the experimenter is aware a priori that neutrons are the only particles entering the instrument being used. Some observations of thunderstorm neutrons were executed with gas-discharge detectors covered with thick lead layers absorbing the primary thunderstorm high-energy electrons and bremsstrahlung gamma rays. In this case, along with the thunderstorm neutrons, photonuclear neutrons produced in lead layers are detected. Only thunderstorm neutrons were assumed to be detected in observations carried out with bare detectors. However, in this case, the primary thunderstorm emissions are detected along with the neutrons.

In any case, gas-discharge detectors conventionally used to measure thunderstorm neutrons, be they shielded or not, do not allow *directly* separating thunderstorm neutrons *in situ* from the primary radiation, i.e., high-energy electrons and γ-rays [31, 98, 99]. Neutron generation is accompanied by the generation of high-energy electrons and γ-rays; moreover, neutrons are produced by these emissions, which are capable of causing the same ionization effects in the detectors as the products of reactions with the neutron participation. Thus, in conventionally used gas-discharge helium (reaction $3\mathrm{He}(\mathrm{n},\mathrm{p})^3\mathrm{H}$) and boron (reaction $^{10}\mathrm{B}(\mathrm{n},\alpha,\gamma)^7\mathrm{Li}$) counters, protons, tritons, α-particles, γ photons, and lithium nuclei ionize the gas to produce an electric pulse in counters, which is then recorded. Therefore, as the instruments are employed in mixed electron-gamma-neutron fields, reliable selection of neutrons is required. As noted in [98, 99], for this purpose, conventionally, two methods are used: the time-of-flight technique, allowing *in situ* separating of neutrons from γ rays and relativistic electrons, and neutron indicators. The first technique selects neutrons by their later arrival at an observation site and, consequently, the later recording of their signals, as the neutrons are slower than gamma photons propagating at the speed of light in free space. Neutron indicators are neutron-produced nuclear reactions with radioactive but rather long-lived daughter products. Detecting the delayed emissions of these products after removing the detector from the mixed radiation field or after termination of the primary pulse of high-energy electrons and bremsstrahlung gamma photons allows being sure that neutrons are detected.

Our analyses [98, 99] of the detecting of the 'extraordinary high flux of low-energy neutrons' reported in paper [40] raised strong doubts as to whether the observed increases in the count rates in helium counters can be attributed to neutrons. Results of Monte Carlo simulations of gamma-ray transport, executed without a priori assumptions and using only data on the experimental configuration in [40], which, instead of analyzing directly measured absolute count rates, allows a comparison of the relative count rates by shielded and unshielded counters, thus verifying the species of the detected radiation, demonstrated that in [40], most likely, hard gamma radiation with photon energies $\varepsilon_\gamma > 1$ MeV was detected. On the other hand, numerical simulation allowing for the sensitivity of the detectors to various radiations shows that neutrons, nevertheless, were registered [41, 42].

Thorough analyses by Tsuchiya [101] allowing for the helium counter spectral sensitivity prove the counter's ability to detect thundercloud-related gamma rays rather than neutrons if surrounded by thick materials. The author of [101] believes that it would be rather difficult to conclude that the signals from helium counters during a thunderstorm are all attributable to thunderstorm neutrons. For a conclusive answer as to whether detected counts are dominated by neutrons or gamma rays, it is necessary to allow for the source altitude and impacts of surrounding matter on the count rates. Based on the results of his analyses, Tsuchiya concludes that the large count rate increases reported in Ref. [40] are due to gamma radiation with photon energies $\varepsilon_\gamma > 10$ MeV from a nearby source in the thunderclouds.

Monte Carlo simulations executed in connection with observations of thunderstorm high-energy emissions at the Yangbajing Cosmic Ray Observatory showed that gamma radiation with photon energies above 10 MeV largely contributes to the NM64 neutron monitor signals, while the contribution of photonuclear neutrons with energies above 1 keV is relatively small [31]. This result suggests that count rate increases from neutron monitors during thunderstorms are not necessarily clear evidence of thunderstorm neutron production. The authors of [31] make a very important conclusion concerning the unreliability of thunderstorm neutron detection with instruments embedded in polyethylene and lead layers. As neutrons interact with these layers, the current signals in the counters do not carry direct information about the incident neutrons. From this, in [31] a conclusion follows that the conventional belief that neutron monitors are not sensitive to gamma radiation because of thick lead blocks absorbing the gamma radiation is groundless.

The authors of [31] point out that thunderstorm high-energy gamma photons produce photonuclear neutrons in the lead, producing additional background, which may be higher than the signal due to the thunderstorm neutrons; hence, it is not clear a priori if the monitor's signals are due to thunderstorm neutrons or to the primary γ rays. As the fluxes of primary high-energy electrons and gamma photons are more intensive than those of the daughter neutrons, and electron ε_e and photon ε_γ energies greatly exceed the photo-neutron energies $\varepsilon_n = \varepsilon_\gamma$ (or ε_e) $- \varepsilon_{th}(\gamma, 1n)$, the conclusion that not neutrons but gamma radiation may dominate increases in penetrating radiations registered by neutron monitors in thunderstorm times [31] is not groundless, in spite of the NM64 detection efficiency of neutrons being higher than that of gamma radiation (cf. Fig. 5).

It seems safe to believe that the delayed coincidence technique Kuroda et al. used in [45] is free from the above shortcomings and allowed directly selecting neutrons *in situ* from electrons and gamma rays. Even more reliable is the approach by Bowers et al. [106], in which the characteristic line in the registered spectrum of the secondary gamma radiation as a signature of primary thunderstorm photonuclear neutrons interacting with the detector is exposed.

5. Thunderstorm positrons. e^+e^- annihilation line as evidence of thunderstorm neutrons

Obviously, intense fluxes of high-energy thunderstorm gamma radiation are capable of producing significant numbers of positrons, which experience annihilation with the ambient electrons, resulting in radiations in the vicinity of the 0.511-MeV e^+e^- annihilation line. These processes naturally are included in the Monte Carlo codes when executing numerical simulations of RREAs and TGFs [19, 31, 41, 45, 56, 57, 87, 93, 104, 144–149], beginning with the very first studies [144–147]. In connection with the runaway breakdown [150], they are analyzed in the paper by Gurevich et al. [151] predicting the possibility of observing the e^+e^- "...line during intensive discharges in atmosphere." This opportunity was achieved significantly later in [19, 24, 46].

5.1 Observations of thunderstorm positrons in high-mountain conditions

The enhancements of the positron component of secondary cosmic rays during thunderstorms were first observed by Khaerdinov and Lidvansky at the Baksan Neutrino Observatory at the elevation of 1,700 m above sea level (Baksan Valley, North Caucasus, Russian Federation). The detector areas of the Baksan Observatory greatly exceed the areas of detectors of high-mountain observatories in Tien Shan (elevation 3,340 m), Tibet (elevation 4,330 m), and Aragats (elevation 3,250 m), and, all the more, the areas of detectors in missions with aircraft or artificial Earth satellites: 54 m^2 for a registration of the soft component (electrons, positrons, and gamma photons in the energy range of 10–30 MeV) [48, 49, 152, 153] and 200 m^2 and 175 m^2 for a registration of the hard component (μ mesons) with thresholds of 100 MeV and 1 GeV, respectively [49, 152–155]. Such vast areas of the detectors allow executing observations of thunderstorm effects with a quite high statistical accuracy.

In 2000–2003, effects of the on-ground electric field during thunderstorms on cosmic rays were observed. Regular variations of the count rate of the soft and hard components of the secondary cosmic rays and sporadic variations (bright events) in the intensity of both components were registered [13, 49, 152]. Khaerdinov and Lidvansky

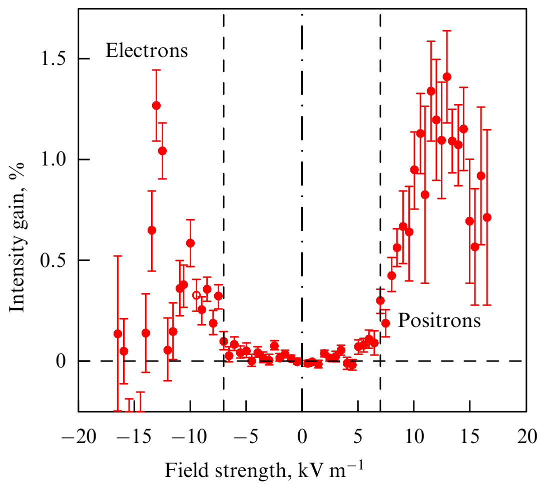

Figure 10. (Color online.) Dependence of the soft component of secondary cosmic ray enhancements upon the on-ground field strength (Baksan Neutrino Observatory) [49].

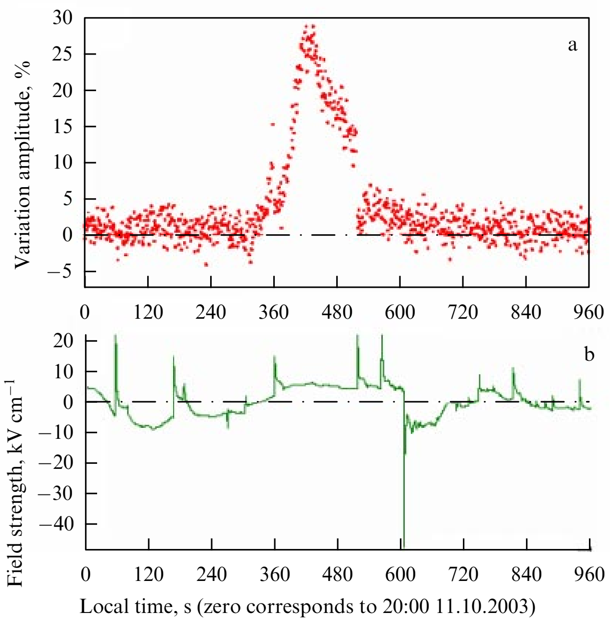

Figure 11. (Color online.) Strong enhancement of the intensity of the soft component of secondary cosmic rays during a thunderstorm on October 11, 2003 (upper panel) and corresponding variations in the on-ground field strength with clearly-seen EMPs of the lightning discharges (lower panel) recorded at the Baksan Neutrino Observatory [49].

emphasize that, though the Baksan Observatory is located at the elevation of 1,700 m, while the height of the surrounding mountains is approximately 3,900 m, thunderstorm electric interferences are observable in spite of extremely low frequency of the bright events: a few events during a storm season [49].

The dependence of intensity variations (deviation from the average daily magnitude) of the soft component, composed of 52 selected thunderstorm events, is illustrated in Fig. 10 [49, 152]. The left part of the figure (negative electric field) corresponds to electrons from secondary cosmic rays obtaining additional energy in the electric field, such that their counting rate was increased. Similarly, the right branch of the figure should correspond to positrons energizing in the field of the opposite sign. It is seen that the change in the spectrum of the on-ground field does not exceed 1.5%. The authors emphasize that the effect is well observable in spite of the fact that the variations in the field strength of 1 kV m^{-1} lead to twenty-fold weaker changes in the count rate than the change caused by an atmospheric pressure variation of 1 mm Hg.

The extraordinarily big enhancement of the soft component (up to 30%) was registered on October 11, 2003 (Fig. 11). The increase occurred within the times of two distant (4.4 and 3.2 km) lightning discharges registered at the moments of time of approximately 360 and 500 s (Fig. 11). The closer discharge, seen in the vicinity of 610 s in Fig. 11, did not affect in any way the intensity of the particles. The authors believe that a source of this increase was located in an area rather distant from the observatory and conclude that such big intensity variations cannot be caused by energy spectrum variations due to the simple acceleration of electrons and positrons in the thundercloud field, so that the generation of additional particles is required.

The duration of this event, more than two minutes, exceeding that of typical TGFs by orders of magnitude, corresponds to the duration of high-energy thunderstorm radiations identified as gamma glows [18, 19]. According to a model Khaerdinov and Lidvansky developed in the framework of the deterministic approach, such events are related to rather prolonged, albeit localized, high-altitude discharges with positive feedback via positrons [48, 49, 156–158]. The minimal field intensity required for this process, obtained allowing for the angular scattering of electrons, exceeds the critical field intensity of the conventional theory of the runaway breakdown, which is equal to the minimum of the electron drag force $F_{\min} \approx 218$ keV m^{-1} atm^{-1} with the scattering omitted (Fig. 1), by only 30%. The minimum of the corresponding drag force is reached at the electron energy close to 10 MeV, which is the energy threshold in observations of the soft component. This process is more localized than the simple cascade multiplication of runaway electrons, for which the extended domain with a sufficiently strong field (many characteristic lengths of RREA amplification by e times) is required. Moreover, it is the only process capable of accounting for the prolonged duration of observed events. Note that the stochastic numerical simulation of RREA and its emissions [19, 31, 41, 45, 56, 57, 87, 93, 104, 144–149] is carried out allowing for all elementary interactions of electrons, including elastic and inelastic angular scattering without the use of the drag force concept. Such simulations self-consistently include all particles of the 'soft component': electrons, photons, and positrons.

5.2 Registration of the thunderstorm e^+e^- annihilation line in near space

In papers [108, 146, 159, 160], it is shown that some portion of the flux of high-energy runaway electrons comprising RREAs is capable of escaping into outer space and contribute, along with RREA bremsstrahlung gamma photons, to the readings of instruments aboard satellites. A source of such combined TGF-like gamma-ray and electron flashes is located at altitudes of 14–15 km [161, 162]. They were observed by Briggs et al. [24] aboard the Fermi satellite launched on July 11, 2008 with the Gamma-ray Burst Monitor comprising fourteen scintillation detectors: twelve with NaI(Tl) crystals covering the energy range from about 8 keV to 1 MeV and two with bismuth-germanate ($Bi_4Ge_3O_{12}$) crystals covering the range from about 0.2 MeV to 40 MeV incapable of distinguishing photons and electrons. The authors of [24] note the extraordinarily prolonged duration of the majority of such TGF-like events and the softer spectrum than that of typical TGFs: their duration is 10 ms longer (Fig. 12) and the spectra are limited to the energy of ≈ 10 MeV, whereas the spectra of the majority of TGFs extend to the region of energies above 30 MeV. These events are a result of high-energy electrons traveling from sources along the geomagnetic field lines. Analyses of the three brightest events revealed that their spectra include strong positron–electron (e^+e^-) annihilation lines in the vicinity of the energy of 0.511 MeV, evidencing that these electron TGFs also contain a substantial positron component (Fig. 13), the fraction of which $N(e^+)/(N(e^+) + N(e^-))$ is estimated to be 0.1–0.3 [24]. Briggs et al. conclude that the pairs are born in conjunction with some lightning discharges and, most likely, all TGFs inject electron-positron beams into space.

5.3 Registration of the thunderstorm e^+e^- annihilation line in a thundercloud

In August–September 2009, a collaboration of seven scientific organizations in the USA carried out observations aboard a

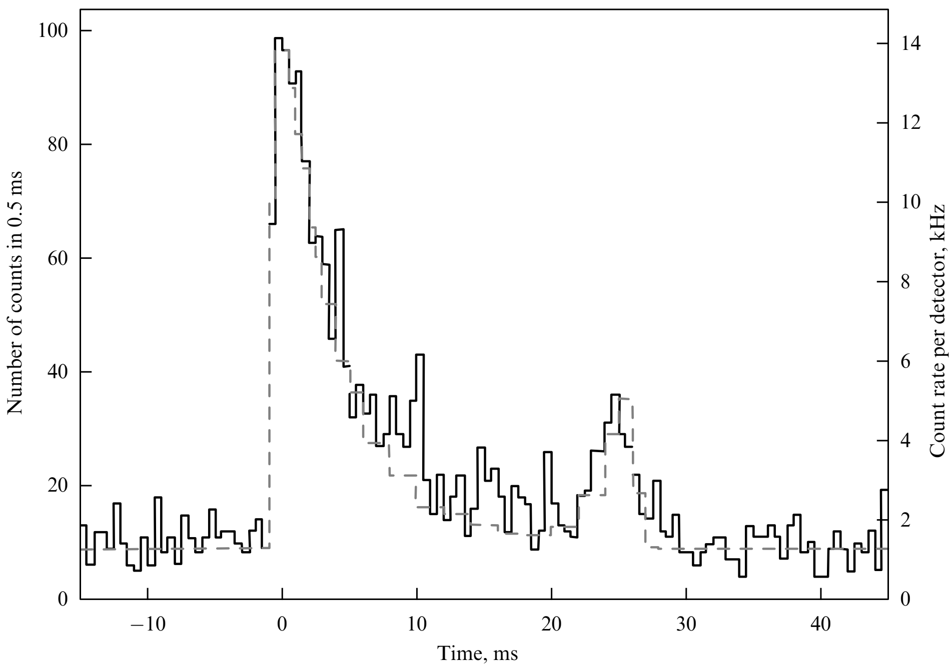

Figure 12. Histogram showing the time history of TGF on December 14, 2009 summed over all 14 detectors aboard the Fermi satellite; the dashed line is the result of Monte Carlo simulations [24].

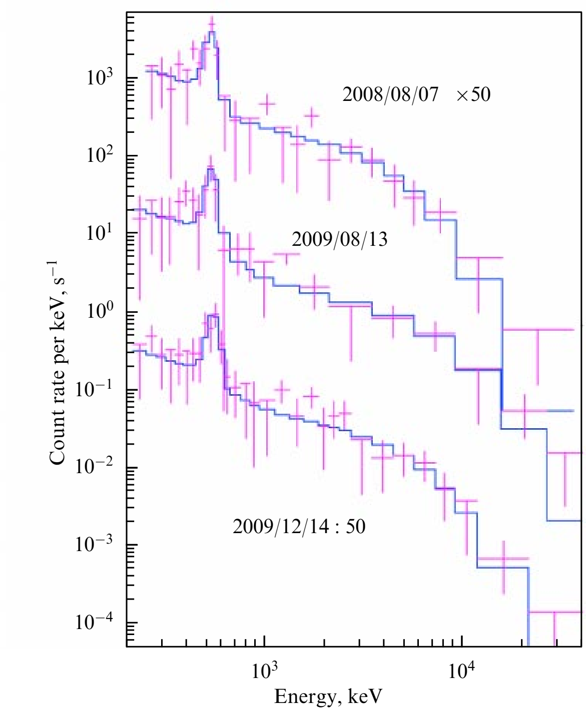

Figure 13. (Color online.) Measured spectral count rate (points with error bars) and numerical model fits (histograms) for the event on August 7, 2008 (labeled 2008/08/07) (50-fold increase), for the event on August 13, 2009 (labeled 2009/08/13), and the first pulse of the event on December 14, 2009 (labeled 2009/12/14) (50-fold decrease) detected aboard the Fermi satellite [24].

Gulfstream V jet aircraft in Colorado and Florida lasting 37 h. Thunderstorm emissions were registered with the Airborne Detector for Energetic Lightning Emissions (ADELE) comprising NaI(Tl) and plastic (BC-408) scintillators with a discrimination of upward and downward moving particles. During nine flights, 12 gamma glows and

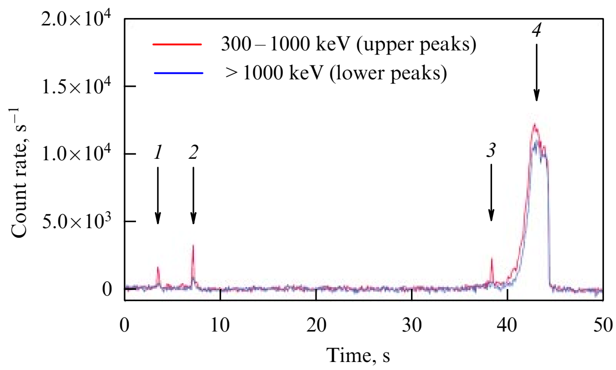

Figure 14. (Color online.) Background-subtracted count rates of the airborne detector ADELE in the 0.3–1 MeV and > 1 MeV ranges [19].

1 TGF correlated with thunderstorms were registered [19, 22]. The most interesting for the question of thunderstorm neutrons is the flight on August 21, 2009, when the plane at the altitude of 14.1 km "...inadvertently entered the upper part of an active thunderstorm cell... ." In this episode, four glows in the energy ranges of 0.3–1 MeV and > 1 MeV were recorded (Fig. 14). The duration of the brightest gamma glow was $\approx$ 5 s with a count rate of $> 10^4$ s^{-1} in both energy ranges. Dwyer et al. [19] suggest that in this event the "...ADELE entered a downward beam of runaway electrons, i.e., the source region of a gamma-ray glow." This glow was preceded by weaker and shorter ones lasting approximately 0.2 s. Two of them, labeled *1* and *3* in Fig. 14, 35 s apart from each other, were almost entirely due to emissions in the 0.511 MeV line. Both increases were approximately a factor of 12 above the background and were accompanied by electrical activity as measured on the underside of the aircraft. The authors of [19] believe that during these events the aircraft, flying several kilometers in 35 s, was briefly immersed in isolated clouds of annihilating positrons.

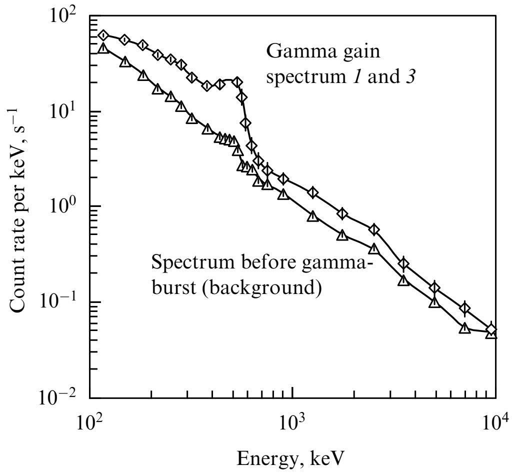

Figure 15. (Color online.) Combined ADELE spectral count rate for times 0–0.75 s before gamma-ray enhancements in peaks *1* and *3* in Fig. 14 (triangles), considered the local background, and combined count rate in enhancements *1* and *3* with the energy of 0.511 MeV recorded during 0.8–0.9 s after the sweep onset in the trigger of each event (diamonds) [19].

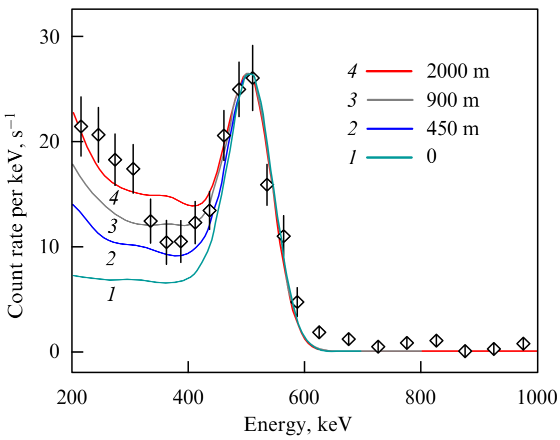

Figure 16. (Color online.) Background-subtracted combined ADELE spectral count rate of two 0.511-MeV enhancements labeled *1* and *3* in Fig. 14 in the time interval of 0.8–0.9 s. Curves *1–4* are results of numerical simulations with positrons filling a volume outside the plane to the radius specified in the figure [19].

Dwyer et al. [19] analyze the events labeled *1* and *3* in Fig. 14 (the events labeled *2* and *4*, for which only crude energy spectra were available from the plastic scintillation detectors, were not analyzed). Figure 15 illustrates combined energy spectra of the events labeled *1* and *3*, obtained with NaI(Tl) detectors. The triangles show the spectrum for the times 0–0.75 s in the records of peaks *1* and *3*, representing the local background during these events. The diamonds are the data of the records for times 0.8–0.9 s after the beginning of the time sweep triggered by each event *1* and *3*.

In Fig. 16, the gamma spectra computed with the Monte Carlo technique for positrons, filling an air volume within the radius shown in the figure, are compared to the measured spectrum in events *1* and *3* [19]. The curve labeled *1* is for the source located immediately outside the aircraft (0 m), such that the interactions of positrons only with materials of the plane and detectors are allowed for. The other curves are for a uniform and isotropic stationary source in the volume specified in the figure by the distance from the aircraft. It is seen that the spectra labeled *1* (0 m, no air) and *2* (interactions both with the plane and detectors and with air at a distance of 450 m are allowed for) are inconsistent with the measured spectrum, producing too few counts at low energies. The spectra computed with large source volumes (radii of 900 m and 2000 m) fit better the measured spectrum, approximately matching both the 0.511-MeV line and the low-energy Compton component.

Thereby, the authors of [19] rule out a local source of positrons in the aircraft vicinity and conclude that the observed enhancements are consistent with being mostly from the emission in the 0.511 MeV line originate in a large volume of air located at a radius of more than 1 km from the aircraft. Because the positron lifetime in a dense atmosphere is orders of magnitude less than 0.2 s, there must be a correspondingly long source of positrons. Dwyer et al. discuss three possibilities without deciding on any of them.

The first source they connect with the possible development of RREA creating electron–positron pairs, the positrons of which run away in a direction opposite to the electron runaway and facilitate the relativistic feedback [56, 57] capable of producing almost arbitrarily large fluxes of positrons [19]. The authors point out two difficulties for this scenario: first, it is not clear how the positrons could move towards the aircraft without producing large fluxes of high-energy photons above 0.511 MeV (such emission was not detected (cf. Fig. 14)), and, second, it is unclear why the *1* and *3* events with the photon energy of 0.511 MeV are very similar.

The second possible source Dwyer et al. [19] connect with a positive leader possibly initiated by the influence of the aircraft, as a result of which the aircraft and ambient atmosphere might acquire a negative charge. In this scenario, cosmic-ray secondary positrons are attracted to the plane, whereas cosmic-ray secondary electrons are repelled, so that positrons are collected close to the plane. But it is not clear how this model explains the generation of a sufficiently strong electric field capable of bringing the positrons in from large distances and, again, why the gamma enhancements at higher energies are small [19].

The third source of positrons, in the opinion of the authors of [19], may be related to the formation of a localized region of enhanced radioactivity inside the thundercloud, possibly created by RREA high-energy electrons and their bremsstrahlung. In fact, as thunderstorms produce neutrons via photonuclear reactions $^{14}N(\gamma, n)^{13}N$ and $^{16}O(\gamma, n)^{15}O$, these reactions, beyond neutrons, produce rather long-lived radioactive isotopes ^{13}N (half-life $\tau_{1/2} = 598$ s) and ^{15}O ($\tau_{1/2} = 122$ s), which undergo β-plus decay $^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$ and $^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$. To overcome the difficulty that in this scenario the RREAs would produce large increases at higher energies, which was not observed, the authors assumed that "...the avalanches must have occurred earlier, before the aircraft was in the vicinity." On the other hand, since the half-lives of ^{13}N and ^{15}O exceed by orders of magnitude the 0.2 s duration of the observed enhancements with photon energies of 0.511 MeV, "...there would be a need for bringing the positrons closer to the aircraft..."[19]. At the same time, it is noted that "...the mobility of ions is too low for them to drift a significant distance during the 0.2 s of the events *1* and *3*, and so the time structure of the event cannot be from the motion of the radioactive isotopes." Another possibility pointed out by the authors of [19] is that the positrons emitted during decays with energies above 1 MeV could run away in fields above the

RREA threshold, traveling large distances from their source; however, the same difficulty remains with the lack of bremsstrahlung photons of energetic positrons.

It is necessary to keep in mind that the small (in comparison with the half-lives of the ^{13}N and ^{15}O isotopes) measured duration of events *1* and *3* may be due to the fact that "...aircraft motion convoluted spatial and temporal effects" as McCarthy and Parks noted [51] while analyzing results of their own observations [5, 6]. The Gulfstream V jet with ADELE could appear at distances sufficiently small for signal registration only at the end of the decay of the ^{13}N and ^{15}O nuclides formed when the plane was rather far away from the domain with enhanced radioactivity; the lack of high-energy gamma radiation in events *1* and *3* possibly testifies to this. Even if the plane was not far from this domain, the duration of the signals recording was limited to the sensitivity of the detectors, and the recorded duration, 0.2 s, of events *1* and *3* is limited by the time during which the irradiation of the detectors was sufficiently intense.

Thus, the mechanism of thunderstorm gamma pulses with the domination of the emission at the line 0.511 MeV detected with ADELE remains unclear. It is unclear even how the positron clouds were created within the thunderstorm cell; Dwyer et al. note that "...it is possible they were caused by the presence of the aircraft in the electrified environment" [19].

5.4 Registration of the thunderstorm e^+e^- annihilation line at sea level

In 2017, the collaboration GROWTH (Global Relay of Observatories Watching Transients Happen) of ten Japanese scientific organizations published long-expected reliable experimental evidence that neutron-producing nuclear reactions do occur in a thunderstorm atmosphere [46]. The observations were carried out in the winter of 2016–2017 on the coast of the Sea of Japan at an elevation of 30–40 m a.s.l. near the Kashiwazaki-Kariwa (Niigata) atomic power plant at the same site where prolonged thunderstorm gamma-ray flashes were first observed with the spectrum extending up to 70 MeV [28].

Three detectors with $Bi_4Ge_3O_{12}$ scintillation crystals (A, B, C in Fig. 1 of Ref. [46]) and one detector with an NaI(Tl) crystal (D in the same figure [46]) were used. On February 6, 2017, two lightning discharges from a thundercloud to the sea surface 0.5–1.7 km from the detectors were registered. The negative discharge with a peak current of -33 kA was followed after 23.7 μs by a positive one with a current of $+44$ kA. All detectors and nine monitors (Fig. 1 in [46]) of the power plant recorded an extraordinary powerful TGF-like radiation flash with a duration of less than 1 ms, which was followed by a gamma afterglow as a result of the capture of neutrons (n, γ) by the nuclei of the atmosphere and Earth's surface. The afterglow detected within intervals of time $40 < t < 100$ ms and $20 < t < 200$ ms, respectively, by detectors A and C exceeded the background by 2–3 orders of magnitude and exponentially decreased over approximately 100 ms with a decay constant of 40–60 ms (Fig. 17). It was followed by an emission in the close vicinity of the γ-line, $\varepsilon_\gamma = 0.511$ MeV, recorded by detectors A and D for one minute (Figs 18 and 19).

Discussing the obtained results, Enoto et al. [46], following the authors of Ref. [19], focused their attention on the fact that, besides neutrons, photonuclear reactions produce unstable isotopes, which via β-plus decay are converted into stable ones over a rather prolonged time.

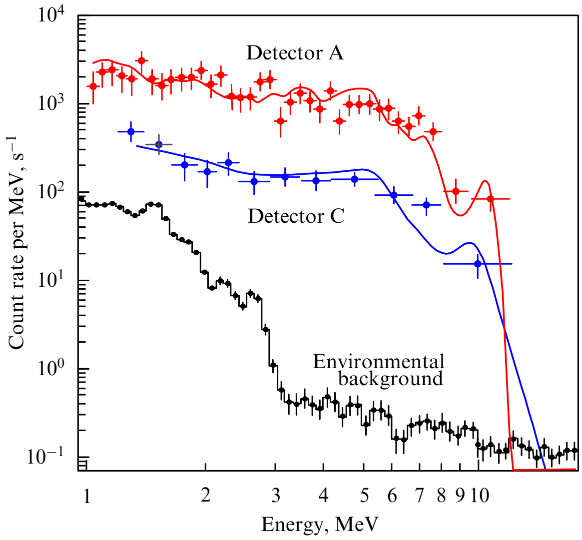

Figure 17. (Color online.) Sub-second spectral count rate of gamma de-excitation of nuclei detected on February 6, 2017 on the coast of the Sea of Japan after a TGF-like flash (duration < 1 ms) by detector A in the time range $40 < t < 100$ ms and detector C in the range $20 < t < 200$ ms [46].

The emitted positrons then annihilate with electrons of environmental atomic particles with the emission of two γ-photons with the energy of 0.511 MeV. Hence, according to Enoto et al. [46], it is possible to prove *experimentally* that the intensity of neutron-producing photonuclear reactions is really increased during thunderstorms, at least by resolving this γ-line in time and energy.

Detectors A and D registered a gradually faded out signal with a characteristic time of ≈ 5 s (decaying component in Fig. 18). After Gurevich and co-authors, who by means of numerical simulations demonstrated that thunderstorm neutrons are generated, basically, in the solid substance around the detectors and directly in the detectors themselves, but not in air [41, 42], the authors of [46] associate this signal with photonuclear reactions $^{28}Si(\gamma, n)^{27}Si$ and $^{27}Al(\gamma, n)^{26}Al$ in the substance surrounding the detectors, in the detectors themselves, and in their cases, because the half-lives of the unstable isotopes ^{27}Si ($\tau_{1/2} = 4.15$ s) and ^{26}Al ($\tau_{1/2} = 6.25$ s) in reactions $^{27}Si \to {}^{27}Al + e^+ + \nu_e$ and $^{26}Al \to {}^{26}Mg + e^+ + \nu_e$ are consistent with the mentioned characteristic time of 5 s. Note that, as the duration of 10–20 s of the portion of the count rate increase, which Kuroda et al. extracted from the 200-s-long burst recorded on January 5, 2012 and which they relate to thunderstorm neutrons [55], is close to ^{27}Si and ^{26}Al half-lives, most likely, the neutrons in this event were also produced in a solid substance.

Along with the decaying signal, detector A registered a delayed component (Fig. 18a), which Enoto et al. attribute to the reactions $^{14}N(\gamma, n)^{13}N$ and $^{16}O(\gamma, n)^{15}O$ in the thundercloud [46]. Unstable products of these reactions, i.e., nitrogen ^{13}N ($\tau_{1/2} = 598$ s) and oxygen ^{15}O ($\tau_{1/2} = 122$ s) isotopes, decay via the reactions $^{13}N \to {}^{13}C + e^+ + \nu_e$ and $^{15}O \to {}^{15}N + e^+ + \nu_e$. Based on this, the authors of [46] arrived at the conclusion that the delayed component is a consequence of e^+e^- annihilation in a cloud filled with positrons and transferred by the wind with a velocity $v_{wind} \approx 17$ m s^{-1} with a characteristic time coinciding with the position of the decay signal maximum $t_{peak} = (34.5 \pm 1)$ s in Fig. 18a, because the product $v_{wind}\, t_{peak} \approx 590$ m is comparable with the distance between detector A and a

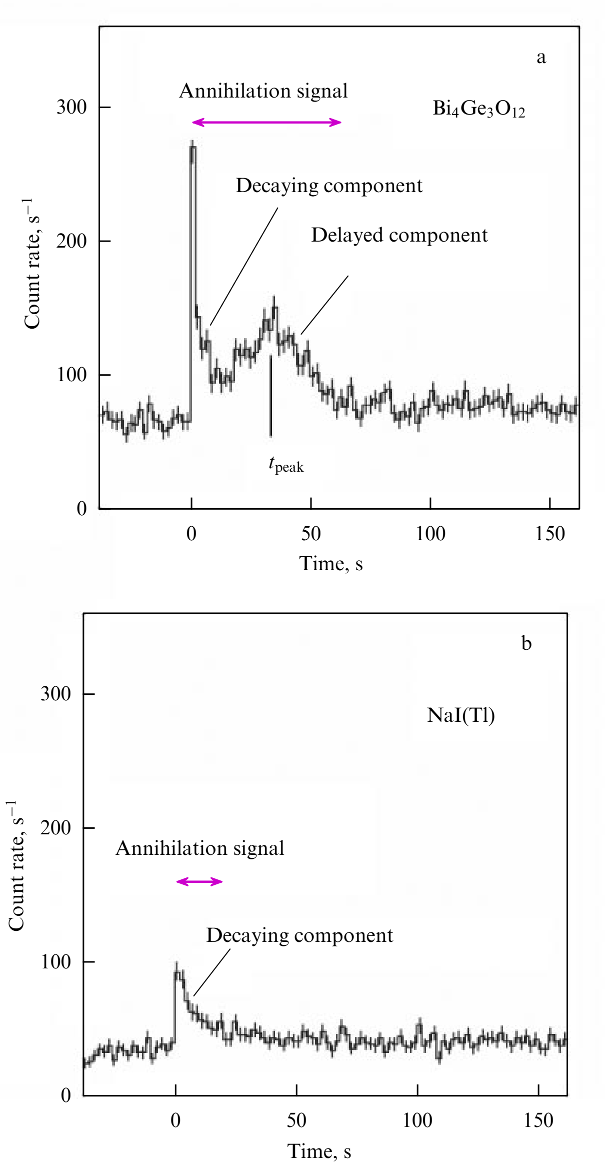

Figure 18. Annihilation signals from detectors (a) A ($Bi_4Ge_3O_{12}$) and (b) D (NaI(Tl)) detected on February 6, 2017 on the coast of the Sea of Japan [46].

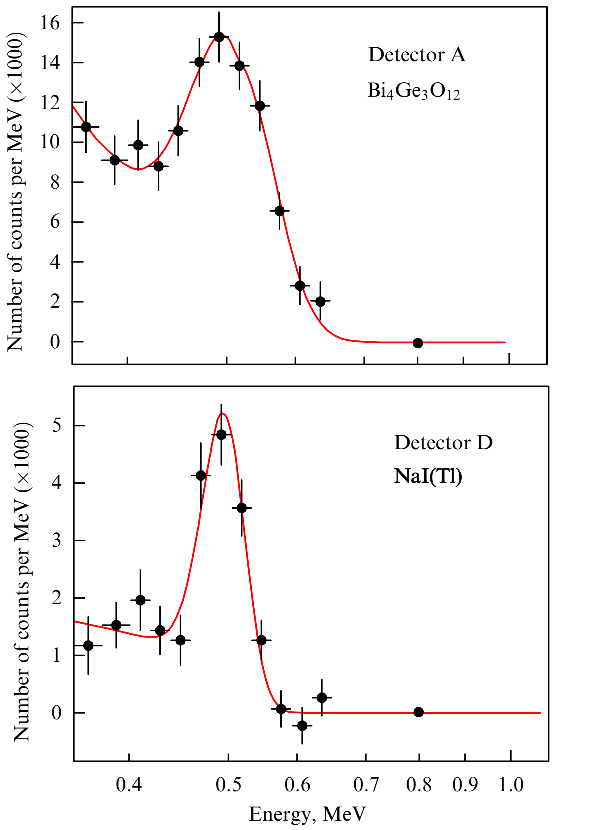

Figure 19. (Color online.) Spectra of the annihilation signals in Fig. 18 [46].

locus of the sea surface struck by the lightning discharges [46]. So, as a matter of fact, the technique of long-lived neutron indicators was implemented with the use of environmental 'detectors', namely, nuclei of atmosphere and the solid substance surrounding the scintillators.

Like the authors of paper [19], Enoto and colleagues [46] do not ignore the possibility of the direct production of electron–positron pairs by high-energy bremsstrahlung γ-radiation in the process of thunderstorm RREA development, but, like the authors of paper [19], they emphasize that the annihilation signals (Figs 18 and 19), which are much more prolonged ($\gg 1$ s) than the signal of gamma de-excitation of the nuclei (Fig. 17), "...were not accompanied ... by γ-rays with energies above 3 MeV" [46]. The duration of each component of the annihilation signal (Figs 18 and 19), especially the delayed component, surpasses by orders of magnitude the duration, ~ 10 ms, of the combined pulses of gamma radiation, electrons, and positrons caused by thunderstorm activity, registered aboard the Fermi satellite, also containing the annihilation component (Figs 12 and 13). Moreover, Enoto et al. [46] noted that during the annihilation signals the environmental electric field on the ground was upward-directed with a strength less than ≈ 3 kV m^{-1} and, therefore, the positrons produced directly by the RREA bremsstrahlung should not have accumulated towards the ground and the annihilation line should not have been enhanced. So, based on these data, Enoto et al. conclude that photonuclear reactions are the straightforward interpretation of the observed annihilation signals.

A similar annihilation signal was registered on the same site on January 13, 2012 [47]. During this event, only detector D was in operation. Enoto et al. [46] consider the obtained result not quite trustworthy, as the neutron signal was spoiled by the detector undershoot and, consequently, a record of the sub-second de-excitation of the nuclei was not carried out due to the impossibility of data acquisition for 200 ms. Even worse, at this time the electric field monitor did not operate, so it is impossible to completely rule out the direct production of pairs by bremsstrahlung photons with energies of 10–20 MeV. Enoto et al. emphasize that, in the event on February 6, 2017, the electric field measured near detector D was negative during the delayed annihilation signal, "...which implies that electrons moved to the ground away from negatively charged clouds, and, consequently, the 0.511-MeV line generation without emitting 10–20 MeV bremsstrahlung photons was thus impossible" [46].

In Fig. 20 [46, 163, 164], channels beginning with the reaction $^{14}N(\gamma,n)^{13}N$ are illustrated. Channels beginning with the reactions $^{16}O(\gamma,n)^{15}O$, $^{28}Si(\gamma,n)^{27}Si$, and $^{27}Al(\gamma,n)^{26}Al$ are similar.

(1) A gamma-photon with an energy above the photonuclear threshold $\varepsilon_{th,N}(\gamma,n) = 10.55$ MeV knocks out a

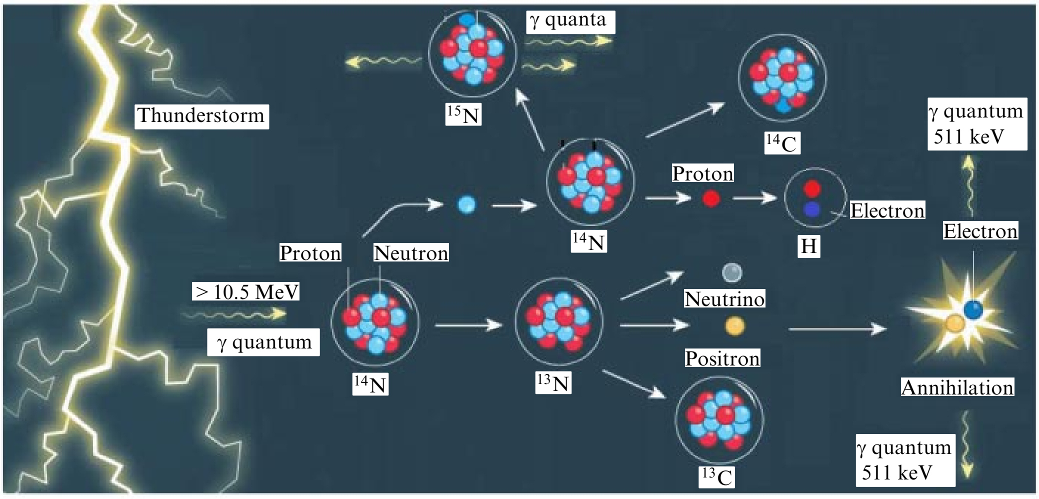

Figure 20. (Color online.) Channels of reactions with the participation of ^{14}N nuclei initiated by a gamma photon with the energy above the photonuclear threshold [46, 163, 164].

neutron from the nucleus ^{14}N; as a result, eventually, a nucleus of the stable isotope ^{13}C is produced, and two annihilation γ-photons with $\varepsilon_\gamma = 0.511$ MeV are emitted.

(2) The knocked-out neutron is captured by the ^{14}N nucleus; after de-excitation by the gamma radiation, a nucleus of the stable isotope ^{15}N is produced. In addition, the birth of a nucleus of the stable isotope ^{17}N after the capture of the neutron by ^{16}O nuclei and de-excitation is possible (not illustrated in Fig. 20).

(3) Another result of the neutron capture by ^{14}N nuclei is that, after daughter nucleus ^{15}N de-excitation via proton emission, a nucleus of weakly radioactive radiocarbon ^{14}C is produced (reaction $^{14}\mathrm{N(n,p)}^{14}\mathrm{C}$). The emitted proton captures a free atmospheric electron to form a hydrogen atom.

6. Consequences of the discovery of the thunderstorm electron–positron annihilation line

(1) Neutron-producing nuclear reactions correlated with lightning discharges really occur in a thunderstorm atmosphere. Thunderstorm neutrons are produced by high-energy photons in TGF-like events and are observable on Earth's surface.

(2) As predicted in [79], thunderstorm neutrons are produced by photonuclear reactions. The detection of the long-lived (tens of seconds) delayed component of the $\varepsilon_\gamma = 0.511$-MeV line after a lightning discharge (typical duration of the return stroke: ~ 50 μs) and γ-flash with a duration of less than 1 ms is trustworthy evidence of e^+e^- annihilation and unequivocal proof of neutron-producing photonuclear reaction occurrences in a thunderstorm atmosphere because the delayed component of the $\varepsilon_\gamma = 0.511$-MeV line is most likely a consequence of the β-plus decay of their long-lived products ^{13}N ($\tau_{1/2} = 598$ s) and ^{15}O ($\tau_{1/2} = 122$ s), produced by photonuclear reactions with the participation of the main components of the atmosphere [46].

(3) It is noteworthy, as theoretically shown in papers [79, 97–100, 110–112], that the reactions of nuclear synthesis do not occur in lightning channels and, hence, cannot be responsible for atmospheric neutron flux increases during thunderstorm activity. This is proven to be true thanks to the results of Ref. [46]: if nuclear synthesis was a cause of thunderstorm neutron production, then the e^+e^- annihilation line $\varepsilon_\gamma = 0.511$ MeV would be absent and photon energies in the (n, γ)-afterglow would be limited to the magnitude of 2.45 MeV (the energy of neutrons in the $^2\mathrm{H}(^2\mathrm{H,n})^3\mathrm{He}$ reaction), while the afterglow spectrum is stretched above 10 MeV (Fig. 17).

(4) The results of Ref. [46] allowed unveiling a previously unknown natural source of isotopes in atmosphere, in addition to the irradiation of Earth by cosmic rays, such as ^{13}N, ^{15}N, ^{15}O, ^{17}O, ^{13}C, and ^{14}C, the latter being widely used in the dating of archaeological artifacts and artworks. Of course, the contribution of thunderstorms to Earth's abundance of the ^{14}C isotope can be comparable in some regions on Earth to that of cosmic irradiation [164]. Future studies should check whether thunderstorms produce other isotopes (e.g., those of hydrogen, helium, and beryllium). Given the significance of the issue, more accurate and numerous experimental studies of thunderstorm gamma radiation and neutrons are required at different altitudes, longitudes, and latitudes.

(5) Thunderstorm-induced nuclear reactions probably occur in the atmospheres of other planets, such as Jupiter, Saturn, or Venus, and might therefore contribute to the isotopic composition of these atmospheres [80, 165]. Determining the magnitude of this contribution will require detailed observations of thunderstorm gamma-ray and neutron flashes on these planets.

(6) The results of the observations in [19] and [46] prove the opinion that thunderstorm neutrons are not generated inside lightning channels, because even the total ranges of γ photons and, all the more, the ranges of photons participating in photonuclear reactions, i.e., photons with energies above the photonuclear threshold $\varepsilon_{\mathrm{th,N}}(\gamma, \mathrm{n})$, exceed by orders of magnitude the transversal sizes of the channels [96–100, 162]. Hence, contrary to the expectations in [69, 75], thunderstorm neutrons do not provide any information on the parameters of the plasma of lightning discharges. Nevertheless, they may deliver information about processes in a thunderstorm atmosphere, because they are produced not only in solid matter on the ground but also in thunderclouds, as is proven by the spectra in

Figs 15 and 16 [19] and the delayed annihilation line in Fig. 18a [46].

7. Conclusions

Research on the high-energy processes in thunderclouds and during thunderstorms, which was started almost a century ago by Charles Wilson [3], remains a new and poorly elaborated field of atmospheric electricity. Though the number of observations of thunderstorm X-ray, γ-ray, and neutron pulses is rather limited, it is now firmly established that high-energy processes are common for terrestrial thunderclouds and thunderstorms and are the consequences of the avalanche-like multiplication of high-energy electrons in the process by Gurevich–Milikh–Roussel-Dupré [55] in large-scale thundercloud fields, as Wilson predicted [3], or in spatially localized electric fields of lightning leaders (e.g., [69, 127, 165, 166] and references therein). Because electrified clouds and lightning discharges are observed in the atmospheres of other planets of the Solar System, and runaway electrons and their bremsstrahlung are observed in electric discharges not only in the air but also in other gaseous media (e.g., [69, 167, 168] and references therein), high-energy phenomena are also most likely common in other planetary atmospheres [80, 165].

Despite the significant success achieved since Wilson's time, especially during the last few decades, little is known about thunderstorm high-energy processes. Among them, nuclear reactions, including neutron-producing ones, have especially been poorly studied. So far, only a few papers reporting on observations of thunderstorm neutrons are available; even fewer are the number of reports on measurements of neutron numbers, such that this magnitude has remained rather uncertain. Conclusions are based on very limited information.

Now, it is not even clear if neutrons are produced by each thundercloud with a sufficiently high charge or each sufficiently strong thunderstorm. So, in the first report claiming the discovery of thunderstorm neutrons in the Himalayas [77], only 124 events with thunderstorm-produced neutrons were selected above the background of 11,200 lightning EMPs. Later, using the same setup, thunderstorm neutrons were observed correlated almost with each registered EMP [86]. According to the vast amount of observational data obtained on Aragats Mountain since 2009, gamma photons with energies above the threshold of photonuclear reactions in atmosphere $\varepsilon_{\mathrm{th,N}} = 10.55$ MeV are produced by each thunderstorm [33–38]. On the other hand, the observations by Alexeenko et al. [169] carried out at various geographical points (Moscow, Obninsk, Baksan in the North Caucasus, Italy; elevations of 200, 175, 1700, and 1000 m, respectively) using detectors with sensitive areas of $S_{\mathrm{eff}} = 0.36-0.75$ m^2 did not reveal any evidence of neutron flux enhancements during thunderstorms. As the data in Table 1 contradict this negative result, it would be expedient to repeat the observations [169] at the same geographical points, allowing for the fact that the observations with a positive result were executed using detectors with a significantly larger sensitive area, for instance, YBJNM $S_{\mathrm{eff}} \approx 32$ m^2 [31], ArNM $S_{\mathrm{eff}} \approx 18$ m^2 [33], LFGNM $S_{\mathrm{eff}} \approx 3$ m^2 [77, 86]. This is especially expedient in view of the detection of the thunderstorm neutron signature by Bowers et al. [106] and the discovery of the thunderstorm e^+e^- annihilation line by Dwyer et al. [19] and Enoto et al. [46]. It is noteworthy, however, that Bowers et al. [106] registered the thunderstorm neutrons with a detector of smaller area, $S_{\mathrm{eff}} \approx 0.14$ m^2, than in observations by Alexeenko et al., but in a region with severe thunderstorm activity and low thunderclouds.

Nuclear synthesis reactions in lightning channels, with which expected and initially observed neutron flux increases during thunderstorms have been connected, are not allowed by known parameters of lightning discharges and contemporary knowledge of macroscopic and elementary processes hypothetically capable of occurring in lightning plasmas. As gamma radiation with photon energies high above the photonuclear threshold are produced in a thunderstorm atmosphere, now the origin of thunderstorm neutrons conventionally is associated with photonuclear and, to a lesser degree, with electro-disintegration reactions initiated by thunderstorm flashes of high-energy electrons and their bremsstrahlung gamma radiation.

The photonuclear origin of thunderstorm neutrons is proven with numerical simulations. However, in view of the difficulty of selecting the neutrons, in observations with conventional gas-discharge detectors, from other penetrating emissions such as high-energy electrons and gamma-ray photons, trustworthy observational evidence of the neutron production in a thunderstorm atmosphere and their origin had not been available till recently. Likely, Kuroda and coauthors, using the delayed coincidence technique, succeeded in *in situ* selecting neutrons from electrons and gamma rays [45], but it remains unclear whether the neutrons were produced in atmosphere or in solid matter on Earth's surface. Thunderstorm photonuclear reactions in atmosphere have hitherto not been observed conclusively, despite increasing observational evidence of neutrons presumably derived from such reactions. To rule out the effects of electrons and γ rays, crucial observation evidence ('Experimentum cruces' by Bacon) was required.

Convincing evidence of the occurrence of thunderstorm photonuclear reactions was obtained only recently in observations by Bowers et al. [106] and Enoto et al. [46]. In the experiment by Bowers et al. [106], in the secondary emission of a plastic scintillator, the characteristic gamma-line with the photon energy of 2.223 MeV was discovered, a result of the radiative capture of neutrons $H_1^1(n,\gamma)H_2^1$ by hydrogen nuclei in the detector, which is a signature of primary thunderstorm photonuclear neutrons. Enoto and colleagues in the framework of the GROWTH collaboration [46], after the prediction by Gurevich et al. of the possibility of observing the thunderstorm e^+e^- annihilation γ-line with the energy of 0.511 MeV produced during the runaway breakdown in thunderstorm electric fields [151] and observations of this line in thunderclouds [19, 22], discovered at sea level the delayed long-lived e^+e^- annihilation line and, in explaining its origin, took into account, as in [19], other products, beyond neutrons, of photonuclear reactions, namely, unstable nuclei in the air and solid matter of the detectors themselves and their environment. Positrons, emitted by the unstable nuclei of atmospheric components, are annihilated; the resulting e^+e^- annihilation line (the delayed component in paper [46]) is direct evidence of the generation of thunderstorm neutrons and their photonuclear origin.

Certainly, the observational results by Dwyer et al. [19], Bowers et al. [106], and Enoto et al. [46], being unique up to the present time, should not to be considered definitive proof of neutron-producing photonuclear reactions in a thunderstorm atmosphere. Followed by the development of adequate models and computer simulations, numerous observations are required with sufficiently high time resolution, with spatial and temporal localization of the radiations sources, and with selection of the various types of radiation. Especially required are accurate measurements of the energy spectra of emissions, in particular, in connection with the difficulties of the direct registration of thunderstorm neutrons, reliable spectral and temporal selection is required of the thunderstorm e^+e^- annihilation lines produced in the atmosphere, in the detectors themselves, and in solid substances in the environment. As Gurevich and colleagues noted, "Such measurements could lead to quite unexpected results" [42].

Neutron-producing thunderstorm reactions occur outside lightning channels; hence, thunderstorm neutrons are not capable of providing insight into the interior of the channels to obtain information on the parameters of plasmas of lightning discharges. Nevertheless, they may provide information about processes in a thunderstorm atmosphere. The discovery of the gamma-lines of the $H_1^1(n, \gamma)H_2^1$ reaction [106] and e^+e^- annihilation [19, 46] proves that a thunderstorm atmosphere produces gamma radiation with photon energies above the photonuclear threshold in air, $\varepsilon_{th,N} = 10.55$ MeV, and is a strong argument in favor of the process by Gurevich–Milikh–Roussel-Dupré [55], forming the foundation of many aspects of high-energy atmospheric electricity. Further searches for thunderstorm neutrons with more detailed studies of their temporal, spatial, and energy characteristics are capable of shedding light on many issues of atmospheric electricity. It is very promising that the discovery of these secondary γ lines opens "a new way of studying TGFs, which are fairly rare...because a balloon or aircraft-borne detectors could measure signatures of TGFs long after a termination of the TGF" [19].

Acknowledgments

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Readers can access the data presented in the paper via the author by email: leonid.babich52@gmail.com.

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