PHYSICAL REVIEW D **89,** 093010 (2014)

Analysis of fundamental interactions capable of producing neutrons in thunderstorms

L. P. Babich,[1,*,†] E. I. Bochkov,[1,†] I. M. Kutsyk,[1,†] and H. K. Rassoul[2,‡]

[1]*Russian Federal Nuclear Center, VNIIEF, 607188 Sarov, Nizhny Novgorod Oblast, Russia*
[2]*Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, Florida 32901, USA*

(Received 3 July 2013; published 13 May 2014)

Elementary processes capable of producing neutrons in thunderstorms are analyzed. Efficiency is evaluated of nuclear fusion, photonuclear reaction, electrodisintegration, and reaction inverse to the β-decay . An extraordinary strong electric field is required for nuclear fusion to occur in a lightning channel. The inverse to β-decay reactions are too weak. The generation of neutrons in a thunderstorm is connected with photonuclear and, to a lesser degree, with electrodisintegration reactions.

DOI: 10.1103/PhysRevD.89.093010 PACS numbers: 92.60.Pw, 25.20.-x, 25.30.-c

I. INTRODUCTION

Nuclear reactions that are capable of producing neutrons during thunderstorms are of great interest for deepening knowledge of plasma processes in thunderstorm electric fields. In particular, neutron generation could provide valuable information about the lightning mechanism itself. If the nuclear reactions proceed in the channel of the return stroke (the main stage of a lightning), which on the microsecond scale is rather well studied, the information on neutrons would allow obtainment of new data about local magnitudes of temperature, electron concentration, and electric field strength. The first attempt by Fleisher to detect thunderstorm-related neutrons [1] was followed by a number of papers communicating statistically significant thunderstorm-associated increases in the count rates of neutron detectors [2–15]. These events could be considered as a manifestation of the nuclear reactions produced in thunderstorm electric fields as predicted by C.T.R. Wilson [16]. However, the gas-discharge $^3\mathrm{He}(\mathrm{n,p})^3\mathrm{H}$ and $^{10}\mathrm{B}(\mathrm{n};{}^4\mathrm{He},\gamma)^7\mathrm{Li}$ counters were used as neutron detectors [1–15], which are sensitive to any ionizing radiation, not only to the products of the above reactions: protons, tritons, alpha-particles, and γ-photons. Because of this, a contribution of high-energy electrons, γ rays, and positrons generated by thunderstorms [4–6,8,17–23] could dominate in count rates [6,8,24,25]. Hence, the communications about neutron generation in a thunderstorm are not trustworthy, maybe with the exception of the Aragats experiment [4–6] in which high-energy electrons, γ rays, and neutrons were detected separately and simultaneously.

Our analysis is motivated by increasing interest in the neutron generation by thunderstorms. Its main goal is a demonstration that neutrons really are produced in thunderstorms and can be detected in spite of the above concern. We analyze representatives of fundamental interactions possibly relating to the problem considered, though in the range of high energies the characteristic times of strong, electromagnetic and weak interactions are related as $\tau_{\mathrm{str}} : \tau_{\mathrm{el}} : \tau_{\mathrm{weak}} \sim 10^{-14} : 10^{-11} : 1$ [26], and, at first glance, strong interaction dominates. In our analysis we reconsider opportunities of the nuclear fusion and photonuclear reactions. Eventually, we consider neutron-producing electron-induced reactions. These were not taken into account in earlier studies, in spite of the fact that flashes of hard γ rays observed in correlation with thunderstorms [4–6,8,17–23] are only secondary bremsstrahlung of high-energy electrons. The photonuclear and electron-induced reactions are analyzed based on the conception of the relativistic runaway electron avalanche (RREA) [27].

II. NUCLEAR FUSION

A. Nuclear fusion due to the ion heating in the electric field in a lightning channel

After the analysis by Libby and Lukens [28], the expected neutron generation in a thunderstorm was commonly connected with nuclear fusion in lightning channels, first of all, with the $^2\mathrm{H}(^2\mathrm{H},n)^3\mathrm{He}$ reaction. However, the kinetic energy of deuterons is limited by charge transfer reactions in the dense atmosphere to such small magnitudes that nuclear fusion is impossible [29–31]. As doubts remain [7,9,15,32], we, unlike the previous analyses [29–31], where the neutron yield has been calculated, evaluate the field strength required for producing at least one neutron in a lightning channel. Using the formula for the neutron yield N_n of the reaction $^2\mathrm{H}(^2\mathrm{H},\mathrm{n})^3\mathrm{He}$ available in [29–31], the reduced field strength required for producing $N_n = 1$ can be estimated as follows:

$$\frac{E}{P} \approx \frac{\varepsilon_{\mathrm{fus}} N_{\mathrm{L}} \langle \sigma_{\mathrm{t}} \rangle}{\ln[N_L P \cdot 2[\mathrm{H_2O}] \cdot [D] \cdot n_{\mathrm{ion}} S_{\mathrm{ch}} l_{\mathrm{ch}} \cdot \Delta t \cdot \langle \upsilon_{\mathrm{ion}} \sigma_{\mathrm{fus}}(\varepsilon_{\mathrm{fus}}) \rangle]}, \tag{1}$$

---

[*] babich@elph.vniief.ru
[†] nikita.rudko@gmail.com
[‡] rassoul@fit.edu

where $N_{\rm L} \approx 2.7 \times 10^{25}\ {\rm m}^{-3} \cdot {\rm atm}^{-1}$ is the number density of air molecules (Loshmidt's number); P is the pressure (in atm.) at the altitude of interest; $[{\rm H_2O}]$ is the relative concentration of water molecules in the thunderstorm and [D] is the relative concentration of deuterium atoms per hydrogen atom in natural water; $S_{\rm ch}$ and $l_{\rm ch}$ are the cross-sectional area and length of the lightning channel; Δt is a lifetime of strong field in the channel ($\upsilon_{\rm ion} \cdot \Delta t \ll l_{\rm ch}$); $\upsilon_{\rm ion}$ and $n_{\rm ion}$ are the velocity and number density of the deuterium ions; $\sigma_{\rm fus}(\varepsilon_{\rm ion})$ is the cross section for the nuclear fusion reaction; $\varepsilon_{\rm fus}$ is a certain minimum energy of deuterons, below which the fusion is inefficient; $\langle\sigma_{\rm t}\rangle$ is the averaged charge transfer cross section; and $\langle\upsilon_{\rm ion}\sigma_{\rm fus}(\varepsilon_{\rm fus})\rangle$ is the fusion rate averaged over the ion distribution function $f(\varepsilon_{\rm ion}, T) = T^{-1} \cdot \exp(-\varepsilon_{\rm ion}/T)$, where $T = eE/N_{\rm L}P\langle\sigma_{\rm t}\rangle$ [29–31,33].

It is seen that in (1) the E/P weakly depends on the most physical quantities; even the strongest dependence on $\varepsilon_{\rm fus}$ and $\langle\sigma_{\rm t}\rangle$ is only linear. We use (relatively reliable) literature magnitudes of the following quantities: $[{\rm H_2O}] \approx 1.65\%$ (in tropics $[{\rm H_2O}] \approx 4\%$) [34], $[{\rm D}] = 0.015\%$ [34], $S_{\rm ch} \sim (1\text{–}10) \times 10^{-3}\ {\rm m}^2$, $l_{\rm ch} \sim 1\text{–}10$ km, and $\Delta t \sim \Delta t_{\rm light} \sim 50\ \mu{\rm s}$ (typical dimensions and duration of the return stroke) [35–38]. The area $S_{\rm ch}$ is set to be equal, on the order of the magnitude, to the cross-sectional area of the hottest part of the lightning channel, through which the current is transported [36–38]. The magnitudes of other quantities are rather uncertain; therefore, we assess the E/P from below by adopting the following limit values. For the deuteron concentration, we use an absolutely unrealistic magnitude $n_{\rm ion} = N_{\rm L}P \cdot 2[{\rm H_2O}] \cdot [{\rm D}]$, meaning all deuterium molecules in the channel volume $V_{\rm ch} \sim S_{\rm ch} \cdot l_{\rm ch}$ are dissociated and ionized. The averaged fusion rate $\langle\upsilon_{\rm ion}\sigma_{\rm fus}(\varepsilon_{\rm fus})\rangle$ can also be estimated from above by letting $\sigma_{\rm fus}(\varepsilon_{\rm ion}) \approx 10^{-29}\ {\rm m}^2 (\varepsilon_{\rm ion} = 2\text{–}4\ {\rm MeV})$ [39] and $\upsilon_{\rm ion} \approx 2 \times 10^7$ m/s corresponding to these energies. On the contrary, we set $\varepsilon_{\rm fus} = 1.7$ keV; with this energy the ${}^2{\rm H}({}^2{\rm H}, {\rm n}){}^3{\rm He}$ cross section is negligibly small: $\sigma_{\rm fus} = 10^{-36}\ {\rm m}^2$ [40]. The charge transfer cross section of the reaction of interest ${\rm D}^+ + {\rm N}_2 \rightarrow {\rm D} + {\rm N}_2^+$ is $\sigma_{\rm t} \approx (4.25\text{–}12.5) \times 10^{-20}\ {\rm m}^2$ [32] in the energy range above $\varepsilon_{\rm fus} = 1.7$ keV. Note, $\sigma_{\rm t} \approx 12.5 \times 10^{-20}\ {\rm m}^2$ is the $\sigma_{\rm t}$ maximum value achieved at $\sim$10 keV [32]. Even with these conservative magnitudes, strongly underestimating E/P, we obtain from (1) that for producing only one neutron, an extremely strong electric field is required with $E/P > (55\text{–}174)\ {\rm MV}/({\rm m} \cdot {\rm atm.})$. These field magnitudes exceed not only the self-breakdown strength in the atmosphere $E_{\rm br}^{(1)} = 3\ {\rm MV}/({\rm m} \times {\rm atm.})$ [35,36], but even the strength of fields, which are generated in air gaps of a centimeter range with the use of unique high-voltage pulses of hundreds kV with picosecond rise-times, allowing the prevention of the breakdown and early collapse of the voltage (cf. [33,41,42] and citations therein). The above estimation is very conservative relative to all parameters and proves that nuclear fusion due to ion heating electric fields in a lightning channel is absolutely unattainable in the relatively slow process of lightning discharges.

B. Nuclear fusion due to the ion runaway in the locally enhanced field in lightning channel

To avoid the limitation of the deuteron energies imposed by the charge transfer, Fülöp and Landreman addressed the ion runaway in the field, locally enhanced by a plasma space charge [32]. Their work was motivated by communication by Gurevich *et al.* [7] who claimed they had detected an unusually strong flux of low-energy neutrons in correlation with lightning discharges. Fülöp and Landreman argued as follows. Due to local violation of plasma quasineutrality, the field strength in the lightning channel becomes locally equal to $\vec{E}^* = \vec{E} \times (1 - Z/Z_{\rm i})$, where Z is a charge of a tested (runaway) ion and $Z_i = n_i/n_e$ is the "mean ionic charge" [31]. If $Z/Z_i > 1$, the field vector $\vec{E}^*$ is directed against the external field vector $\vec{E}$. Moreover, if $Z/Z_i \gg 1$, the field $\vec{E}^*$ becomes much stronger than the external field. This occurs if a ratio of the local number density of ions to that of drifting electrons is $n_i/n_e \ll 1$ [32]. As a result, a small portion of ions, being involved by the bulk of electrons drifting along $-e\vec{E}$ (where e is the elementary charge), is accelerated "in the direction of the electron streaming" [32] to energies sufficient for the nuclear fusion ${}^2{\rm H}({}^2{\rm H}, n){}^3{\rm He}$. This very interesting idea, promising new insights in the physics of lightning, meets serious difficulties. Next, we outline some particular inconsistencies, stemming from the idiosyncrasies of discharges in dense gases, in general, and lightning, in particular, and then discuss whether a strong violation of plasma quasineutrality in significant domains of the lightning channel is possible at all.

First, we shall discuss whether the mechanism of ion runaway agrees with the limitation of the electric field strength in the atmosphere imposed by the self-breakdown magnitude [35–38]:

$$E_{\rm br} = E_{\rm br}^{(1)} \times P \approx 3\,\frac{\rm MV}{\rm m.atm.} \times P({\rm atm.}) \tag{2}$$

for a homogeneous field. In Fig. 4 in [32], the specific rate of neutron generation is presented as computed in dependence on the reduced strength of the external field $E/(n_a Z_i)$ in the range from about 20 to 200. Allowing for that, in Fig. 4 [32], the strength E is in MV/m units and the number density of neutrals n_a is in units of $10^{24}\ {\rm m}^{-3}$ and, using the Loshmidt's number for the molecular number density, the molecular density at pressure P, in units of $10^{24}\ {\rm m}^{-3}$, can be written as follows:

$$\begin{aligned} n_a &= 2.7 \times 10^{25} ({\rm m}^{-3} \cdot {\rm atm.}) \times P({\rm atm.})/10^{24} (m^{-3}) \\ &= 27 \times P({\rm atm.}) \end{aligned} \tag{3}$$

Therefore, because the external field strength E is limited by the breakdown magnitude (2), the relation

$E = 200 \times n_a Z_{\mathrm{i}} \approx 200 \times 27P(\mathrm{atm.}) \times Z_{\mathrm{i}} < E_{\mathrm{br}}^{(1)} \times P$ is to be satisfied, from which it follows that a limitation,

$$Z_{\mathrm{i}} < 0.5 \times 10^{-3} \tag{4}$$

should be imposed on the mean ionic charge for the data in Fig. 4 in [32] to be valid. The magnitudes $Z_i = 0.001$, 0.01, 0.1, with which particular numerical computations were carried out in [32], are not consistent with the limitation (4). Actually, the $E_{\mathrm{br}}^{(1)}$ magnitude is less than (2) because the process considered (ion runaway) develops in a strongly ionized plasma channel and the field is inhomogeneous; therefore, the limitation to be imposed on Z_i is stronger than (4). In view of $Z_i = n_i/n_e$ [32], the violation of plasma quasineutrality should be significantly stronger than is assumed in [32]. However, even with $Z_i = 0.001$, 0.01, 0.1 and measured thunderstorm field strength $E_{\mathrm{th}} \approx$ 140–1200 kV/m (cf. [36–38] and citations therein), the enhanced field strength $|E^*| = E_{\mathrm{th}} \times |(1 - Z/Z_{\mathrm{i}})|$ for the deuterons ($Z = 1$) is close to or on the orders of magnitude higher than the self-breakdown strength (2).

One more inconsistency in [32] is connected with that, that according to (3), the pressure magnitude $P \approx 1/27$ atm. (altitude $z \approx 23$ km, the middle stratosphere) corresponds to the molecular density $n_a = 10^{24}\ \mathrm{m}^{-3}$ accepted in [32]. However, lightning discharges develop in the troposphere (cf. [36–38,43,44] and citations therein) at pressures of $P(\mathrm{atm.}) \approx \exp(-z/7.1\ \mathrm{km}) \approx (1/2.7 - 1)$, to which magnitudes $n_a \approx (1\text{–}2.7) \times 10^{25}\ \mathrm{m}^{-3}$ correspond. For instance, observations in [7] have been carried out at the altitude where $n_a \approx 1.8 \times 10^{25}\ \mathrm{m}^{-3}$. The neutron yield in [32] was computed using the ion distribution function $f(v_i) = Cf(1 + Bv_{\mathrm{i}}^4)^{-A/4B}$, which with $A = (5/4)(n_a Z_{\mathrm{i}}/E)\,(m_{\mathrm{i}}/Ze)^2 \times 10^{-23}$ [32] strongly depends on n_a. Therefore, using more real magnitude $n_a \approx (1\text{–}2.7) \times 10^{25}\ \mathrm{m}^{-3}$ instead of $n_a = 10^{24}\ \mathrm{m}^{-3}$ [32] strongly cuts off the high-energy tail of $f(v_{\mathrm{i}})$ and, consequently, the numbers of predicted neutrons.

Finally, let us estimate the absolute yield of fusion neutrons from lightning using the highest value of the specific rate of neutron generation $N_n/(V_{ch} \cdot \Delta t) = 10^7\ (\mathrm{m}^3 \cdot \mathrm{s})^{-1}$ in Fig. 4 [32], where V_{ch} is "the volume of the lightning channel" and Δt is "the lifetime of the electric field within the lightning channel" [32]. Actually, in the context of the idea by Fülöp and Landreman, instead of V_{ch}, a small volume of the channel with $n_i/n_e \ll 1$ is to be used. Localized domains at the leader and return stroke fronts satisfy this condition. Judging by the increased brightness, the length of these domains is of $l =$ 25–110 m [36]. In contradiction with their own Δt definition, cited above, the authors wrote that "…quasistable electric fields, lasting tens of minutes can be formed during the mature stage of thunderstorms. Therefore, Δt can vary by many orders of magnitude from 5×10^{-5} s to several hundred seconds" [32]. However, free ions are produced within the channels, not in the large scale field of a thundercloud; therefore, it is correct to set Δt to be equal to the average return stroke duration $\Delta t_{\mathrm{light}} \approx 50\ \mu\mathrm{s}$ [36–38]. Instead of V_{ch} it is reasonable to use a volume equal to the area $S_{ch} \approx (1\text{–}10) \times 10^{-3}\ \mathrm{m}^2$ of the hottest part of the channel cross section multiplied by the length of the domain with the enhanced field $l =$ 25–110 m. In the result, we obtain an undetectable neutron yield of $N_n <$ 100–1000 per stroke.

It is not clear, however, if the acceleration of ions "in the direction of the electron streaming" [32] along $-e\vec{E}$ is possible at all. Electrons are more mobile than ions (the mobility of electrons relates to that of N_2^+ ions as ~50000/1) and, therefore, their reverse motion along $\vec{E}$ ("counter streaming" relative to the flux of tested ions) is capable of preventing a strong violation of the quasineutrality. Hence, the motion of a small portion of electrons during some time Δt along $\vec{E}$, i.e., against the drift of the bulk of electrons towards the hypothetical flux of tested ions, is capable of preventing the local overturning of the electric field and increasing its strength above E. To demonstrate this, it is convenient to use Maxwell's equation:

$$\frac{|\Delta E^*|}{\Delta x} \approx \frac{e}{\varepsilon_0}\left|n_e - n_i\right|, \tag{5}$$

where ε_0 is the permittivity of free space. The displacement of electrons drifting in the field $\vec{E}^*$ with a velocity v_e during time Δt is $\Delta x = v_e \Delta t = (\mu_{\mathrm{e}}/P) \cdot E^* \Delta t$, where μ_e is the electron mobility at 1 atm. In view of $|\Delta \mathrm{E}^*| = |E - E^*| \sim E^*$ for $\mathrm{Z}/Z_i \gg 1$ and $n_i/n_e = Z_i \ll 1$ [32], the equation (4) is reduced to the relation

$$\Delta t \approx \frac{\varepsilon_0}{e(\mu_{\mathrm{e}}/P)n_e} \tag{6}$$

meaning that for the field E^* to be decreased to E, the electrons should counter stream during Maxwellian relaxation time. Here, letting $\mu_e = 0.06\,(\mathrm{m}^2 \cdot \mathrm{atm})/(\mathrm{V} \cdot \mathrm{s})$ [35], $P = 1/27$ atm. [32] and the lowest value in [32] $n_e = 10^{21}\ \mathrm{m}^{-3}$, we obtain $\Delta t \sim 10^{-14}$ s. Actually, the n_e magnitudes are higher: n_e is of 10^{24} during the first 5 μs of the average return stroke development and decreases down to $10^{23}\ \mathrm{m}^{-3}$ during the next 10 μs [36,37]. With these n_e magnitudes and $P = (1/2.7 - 1)$atm., the Δt is of $(10^{-15}\text{–}10^{-16})$ s. In any case, Δt is many orders of magnitude less than the average return stroke duration $\Delta t_{\mathrm{light}} \approx 50\ \mu\mathrm{s}$ [36–38]. On the other hand, with $\Delta t = \Delta t_{\mathrm{light}} \approx 50\ \mu\mathrm{s}$ the relation (6) gives $n_e \approx 5 \times 10^{13}\ \mathrm{m}^{-3}$ and $n_e \approx 5 \times 10^{14}\ \mathrm{m}^{-3}$, respectively, for $P = 1/2.7$ and 1/27 atm. These n_e magnitudes, sufficient to prevent violation of the quasineutrality, are much less than the magnitudes 10^{21}, 10^{22}, and $10^{23}\ \mathrm{m}^{-3}$ used in [32] and especially less than the magnitudes $n_e = 10^{23}\text{–}10^{24}\ \mathrm{m}^{-3}$ in the return stroke. These estimations prove that the backward motion of a small portion of electrons against the direction of the main electron stream would prevent strong violation of the quasineutrality in significant domains of the lightning channel required for the ion runaway to high energies and producing detectable neutron yields due to the nuclear fusion. Note, at the leader fronts the field is stronger than the external field, but both are collinear.

C. Possibility of neutron generation in the hypothetical pinch necks

Extremely long and narrow lightning channels do resemble laboratory plasma pinches. It is known that pinches are unstable relative to the development of necks [45,47]. Strong eddy electric fields, produced in the domain of the necks, are responsible for the observed generation of high-energy charged particles and neutrons [45,46]. The voltage produced in the neck domain can be estimated as follows:

$$U_{\rm neck} = \mu_0 {\rm I} r(\dot{r}/r - \dot{I}/I)/2\pi, \tag{7}$$

where μ_0 is the magnetic permittivity of free space, I is the lightning current, and r is the decreasing neck radius. Unlike the known formula [45], the current variation is taken into account [33]. It is reasonable to let the compression velocity in the neck be equal to Alfven's hydrodynamic velocity $\upsilon_{\rm A} \approx H \times \sqrt{\mu_0/i\rho P({\rm atm.})} = H \times \sqrt{\mu_0 N_L/n_e \rho}$, where $H = I/2\pi r$ is the magnetic field strength, $\rho = 1.33\,P\ {\rm kg}/({\rm m}^3 \cdot {\rm atm.})$ is the air density reduced to 1 atm. and i is the plasma ionization degree. With $I = 50$ kA, $r = 0.03$ m, $n_e = 10^{23}$–$10^{24}\ {\rm m}^{-3}$, and $\dot{I} = 5 \times 10^6$ kA/s [36], we obtain insignificant voltage less than 10 V. Hence, the neck instability does not generate sufficiently high voltage to account for the neuron generation. Variation of I, r, n_e, and $\dot{I}$ magnitudes within reasonable limits does not change this conclusion. Note that even if the voltage would be high enough for the nuclear fusion, the neck volume is too small ($\sim r^3$) to produce significant numbers of neutrons, unless the whole lightning channel consists of numerous necks.

III. PHOTONUCLEAR REACTIONS

Because hard γ rays are generated during thunderstorms [4–6,8,17–23], the photonuclear reactions (γ, Xn) are the most obvious elementary processes capable of accounting for the neutron production [29–31]. Here, X is the neutron number in a particular elementary event. The threshold energies of photonuclear reactions $\gamma(^{14}{\rm N}, 1{\rm n})^{13}{\rm N}$ and $\gamma(^{16}{\rm O}, 1{\rm n})^{15}{\rm O}$ with the nuclei of the main atmospheric components are equal to $\varepsilon_{\rm th,N}(\gamma, 1{\rm n}) = 10.55$ MeV and $\varepsilon_{\rm th,O}(\gamma, 1{\rm n}) = 15.7$ MeV [47]. A meaningful fact is that the average energy of electrons in the RREA, of 6–7 MeV [48–50], is not too much less than $\varepsilon_{\rm th,N}$ (γ, 1n) for the field overvoltages $\delta = eE/(F_{\rm min} \times P) = (eE/P)/(218\ {\rm keV}/({\rm m} \times {\rm atm.}))$ below the self-breakdown limit $\delta \approx 14$ in air. Thunderstorm-correlated γ-ray flashes were observed with spectra extending to energies ε_γ close to or much higher than $\varepsilon_{\rm th,N}(\gamma, 1{\rm n})$: 40–50 MeV [4], above 40 MeV [8], 10 MeV [17,18], above 10 MeV [19], measured respectively at altitudes of 3250 m [4], 4300 m [8], 2770 m [17,18], and 1700 m [19]; above 20 MeV [20], 30–38 MeV [21], and 100 MeV [22], measured in near space; up to $\sim$35 MeV with small errors, and up to $\sim$70 MeV with large errors at sea level [18,23]. It is necessary to keep in mind that γ-ray fluxes in their sources are more intensive and their spectra are much harder than at the detecting instruments. Therefore, neutron production by (γ, Xn) reactions during γ-ray transport in the atmosphere is more efficient than can be predicted on the basis of the measured photon numbers and spectra. Hence, photonuclear reactions, in principle, are capable of producing neutrons in the thunderstorm atmosphere.

Following this idea, yields of (γ, Xn) reactions from thunderstorms have been calculated (cf. [8,51–56] and citations therein). Nevertheless, doubts are being expressed about the capability of photonuclear reactions to account for the neutron flux increases during thunderstorms [7,15,32]. The doubts are based on the communication by Gurevich *et al.* [7], who claimed they detected, in correlation with lightning, an unusually strong flux of low-energy neutrons: "…of the order of (3–5) 10^{-2} neutrons ${\rm cm}^{-2}\,{\rm s}^{-1}$." They claimed that "this flux value constitutes a serious difficulty for the photonuclear model of neutron generation in thunderstorm." Ignoring the above-cited observations of γ-flashes with spectra extending high above the threshold $\varepsilon_{\rm thN}(\gamma, 1{\rm n})$, Gurevich *et al.* wrote "As for the high energies 10–30 MeV [i.e., above $\varepsilon_{\rm thN}(\gamma, 1{\rm n})$], the only work where the flux of the γ-ray emission during thunderstorms was measured from the ground is [4]. The obtained γ-ray emission flux was about 0.04 quanta ${\rm cm}^{-2}\,{\rm s}^{-1}$, 3 orders of magnitude less than the value needed "for explaining the claimed neutron flux." However, integrating the absolute spectrum in Fig. 7 [4] above the $\varepsilon_{\rm th}(\gamma, 1{\rm n}) = 10.55$ MeV, we obtained γ-flux an order of the magnitude higher: $\Phi_\gamma \approx 0.4\ ({\rm cm}^2 \times {\rm s})^{-1}$. Possibly, the estimation $\Phi_\gamma = 0.04\ ({\rm cm}^2 \times {\rm s})^{-1}$ in [7] was obtained with the omitted 10% detector efficiency [4]. More important is that in the communication [4], as in the other communications [8,17–23], the count rates and photon spectra at detectors are presented, not the flux and spectra in the sources, direct measuring of which is impossible and which are required to compute photonuclear neutron yield in the air, in the detector substance and in the surrounding objects. The authors of the paper [15], expressing doubts, only agree with Gurevich *et al.* The analysis by Fülöp and Landreman [32], as mentioned above, was motivated by these observations by Gurevich *et al.*

Actually, as was shown by Monte Carlo simulations [6,24,25], Gurevich *et al.* were most probably detecting not neutrons but, most likely, γ rays and high-energy electrons.

Hence, their doubts and the doubts expressed in [15,32] concerning the photonuclear origin of thunderstorm neutrons are unjustified. Nevertheless, in view of these doubts, we have analyzed, as the most illuminating case, a possibility of generation of photonuclear neutrons by prolonged (of 1 min) bursts of hard γ rays from low thunderclouds detected by Tsuchiya *et al.* at the coast of the Sea of Japan, for which the γ-ray spectrum and fluence $F_\gamma^{\mathrm{exp}} \approx 2 \times 10^4\ 1/\mathrm{m}^2$ were measured at sea level [18,23]. Because absolute numbers of γ-photons and γ-spectrum in the source, not at the detector, are required, while executing Monte Carlo simulations [24,57], we have used for the γ-ray source the computed RREA bremsstrahlung spectrum $f_\gamma(\delta,\, \varepsilon_\gamma)$ normalized to unity [58]. With this spectrum in the source, located at altitudes $z_\gamma^{\mathrm{emis}} \leq 2$ km, the calculated γ-spectrum at sea level [57] excellently fits the measured spectrum [18,23]. Simulating a transport of γ-photons by the Monte Carlo technique down to sea level with subsequent fitting to the measured fluence F_γ^{exp}, we calculated numbers of γ-photons $N_{\gamma,\mathrm{emis}}$ emitted by the source located in the range of altitudes $z_\gamma^{\mathrm{emis}} = 1\text{–}10$ km. The numbers of γ-photons capable of producing neutrons were calculated by multiplying $N_{\gamma\text{-emis}}$ by a portion of γ-photons above the threshold $\varepsilon_{\mathrm{th,N}}(\gamma, \mathrm{In})$:

$$\Delta_\gamma(\delta, \varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n})) = \int_{\varepsilon_{\mathrm{th,N}}(\gamma,1\mathrm{n})}^{\infty} f_\gamma(\delta, \varepsilon_\gamma) d\varepsilon_\gamma. \tag{8}$$

The calculated fluence of photonuclear neutrons at sea level $\sim 2.2 \times 10^3\text{–}2.4 \times 10^4\ \mathrm{n/m}^2$ [24,57] generated by these γ rays during their transport in the atmosphere is sufficient for registration. For instance, much less fluence of $(34-670)\ \mathrm{n/m}^2$ corresponds to the neutron numbers claimed to have been detected by Shah *et al.* [2].

IV. ELECTRON-INDUCED REACTIONS

Thresholds of some of these reactions in air are lower than the photonuclear threshold $\varepsilon_{\mathrm{th}}(\gamma, 1\mathrm{n}) = 10.55\,\mathrm{MeV}$. Only this can make the electron-nucleus interactions more efficient. It is very important to note that electrons directly produce neutrons, unlike the photonuclear reactions requiring the intermediate bremsstrahlung process. Therefore, significant neutron yields can be expected due to electron interactions with atmospheric nuclei. The reaction of electrodisintegration and the inverse to the β-decay reaction $e^-(p^+,\, n)\nu_e$ are considered below. To evaluate absolute neutron yields of these reactions, knowledge of high-energy electron numbers N_e is required. To avoid directly using the unknown N_e magnitudes, we compare yields of electron-nucleus interactions with that of photonuclear reactions and thus clarify the relative efficiency of electron-nucleus interactions. Within the accuracy of the present analysis, it is sufficient to allow for interactions with ${}^{14}_{7}N$ nuclei because of lower concentrations of other air components and larger energy thresholds. The rate of photonuclear neutron generation is estimated as a number of neutrons produced per unit of time along the γ-ray range l_γ [51–55,57]:

$$\begin{aligned}\left(\frac{dN_{\mathrm{n}}(\delta)}{dt}\right)_{\gamma,\mathrm{n}} &= N_{\mathrm{e}} \cdot \frac{dN_\gamma(\delta)}{dt} \cdot 2N_{\mathrm{L}}P \cdot \int_{\varepsilon_{\mathrm{th},N}(\gamma,1\mathrm{n})}^{\infty} f_\gamma(\delta, \varepsilon_\gamma) \cdot \sigma(\gamma, Xn) \cdot l_\gamma(\varepsilon_\gamma) d\varepsilon_\gamma \\ &\approx N_{\mathrm{e}} \cdot \frac{dN_\gamma(\delta)}{dt} \cdot \langle f_\gamma(\delta, \varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}))\rangle \cdot 2N_{\mathrm{L}}P \cdot [N_2] \cdot \sigma_{\mathrm{yield}}(\varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}) \cdot l_\gamma(\varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}), P),\end{aligned} \tag{9}$$

where $dN_\gamma(\delta)/dt$ is the rate of photon emission per one runaway electron (RE), $[N_2]$ is the nitrogen relative concentration in air, $\sigma(\gamma, Xn) = \sum_{\mathrm{i}} i \cdot \sigma(\gamma, i \cdot n) + \nu\sigma(\gamma, f)$, $\sigma(\gamma, in)$ is the cross section of the (γ,*i*n) reaction with a yield of *i* neutrons, $\sigma(\gamma, f)$ is the photonuclear fission cross section with a yield of ν neutrons, $\sigma_{\mathrm{yield}}(\varepsilon_{\gamma,\mathrm{max}}) = \int_{\varepsilon_{\mathrm{th}}(\gamma,1\mathrm{n})}^{\varepsilon_{\gamma,\mathrm{max}}} \sigma(\gamma, Xn) d\varepsilon \approx 98.8\,10^{-31}\ \mathrm{MeV} \times \mathrm{m}^2$ is the total photoneutron yield cross section [47], $\varepsilon_{\gamma,\mathrm{max}} \approx 29.5$ MeV is a maximal energy at which data on the cross section $\sigma(\gamma, Xn)$ are available in [47], and $l_\gamma(\varepsilon_{\mathrm{th,N}}(\gamma, 1n), P)$ is the range of photons with the energy $\varepsilon_{\mathrm{th,N}}(\gamma, 1n)$ at pressure P. We use $dN_\gamma(\delta)/dt \approx 10^7 1/(\mathrm{s} \times \mathrm{atm.} \times \mathrm{RE})$ and $\langle f_\gamma(\delta, \varepsilon_{\mathrm{th,N}}(\gamma, 1n))\rangle > \frac{1}{\varepsilon_{\gamma,\mathrm{max}} - \epsilon_{\mathrm{th,N}}(\gamma,1n)} \int_{\varepsilon_{\mathrm{th,N}}(\gamma,1\mathrm{n})}^{\varepsilon_{\gamma,\mathrm{max}}} f_\gamma(\delta, \varepsilon_\gamma) d\varepsilon_\gamma \approx 5 \times 10^{-4} 1/\mathrm{MeV}$ computed for the RREA in air [58], and $l_\gamma(\varepsilon_{\mathrm{th,N}}(\gamma, 1n), P = 1\,\mathrm{atm.}) \approx 500 = \mathrm{m}$ [34].

A. Electrodisintegration reactions

Two threshold reactions of this kind are relevant to the problem considered:

$${}^{14}_{7}N + e^- + \varepsilon_{\mathrm{e}} \to {}^{13}_{7}N + n + e^-; \tag{10}$$

$${}^{16}_{8}\mathrm{O} + e^- + \varepsilon_{\mathrm{e}} \to {}^{15}_{8}\mathrm{O} + n + e^-, \tag{11}$$

where ε_{e} is the kinetic energy of the incident electron.

The thresholds can be calculated as the mass defect using nuclei masses available, for instance, in handbook [59] or elsewhere. Naturally, they are the same as the $(\gamma, 1n)$ threshold. The threshold of reaction (10),

$$e_{\mathrm{th,N}}(\mathrm{e}^-, \mathrm{n}) = (M({}^{13}_{7}\mathrm{N}) + m_{\mathrm{n}} - M({}^{14}_{7}\mathrm{N})) \cdot c^2 = 10.55\ \mathrm{MeV} \qquad (12)$$

is not too much higher than the average energy of electrons, 6–7 MeV in RREA. We neglect the reaction (11) because of the lower oxygen concentration and higher threshold, $\varepsilon_{\mathrm{th,O}}(\mathrm{e}^-, \mathrm{n}) = 15.7$ MeV.

The electrodisintegration rate of nitrogen nuclei can be estimated as follows:

$$\left(\frac{dN_{\mathrm{n}}(\delta)}{dt}\right)_{\mathrm{e}^-,\mathrm{n}} \approx N_{\mathrm{e}}\left(\varepsilon \geq \varepsilon_{\mathrm{th,N}}(e^-, n)\right) \cdot v_{\mathrm{e}} < \sigma_{\mathrm{e}^-,\mathrm{n}} > \cdot 2N_{\mathrm{L}}P \cdot [N_2], \qquad (13)$$

where $N_{\mathrm{e}}(\varepsilon \geq \varepsilon_{\mathrm{th,N}}(e^-, n)) = N_{\mathrm{e}} \cdot \int_{\varepsilon_{\mathrm{th,N}}(e^-,n)}^{\infty} d\varepsilon_{\mathrm{e}} f_{\mathrm{e}}(\delta\varepsilon_{\mathrm{e}}) \approx 0.008 \cdot N_{\mathrm{e}}$ is the RE number above the threshold (12); $f_{\mathrm{e}}(\delta\varepsilon_{\mathrm{e}})$ is the RE universal distribution function, almost independent of δ [48–50]; $v_{\mathrm{e}} \approx 2.7 \times 10^8$ m/s is the RE velocity [48–50]; and $\sigma_{\mathrm{e}^-,\mathrm{n}}$ is the cross section of reaction (10). The (13)-to-(9) ratio is as follows:

$$\left(\frac{dN_{\mathrm{n}}(\delta)}{dt}\right)_{\mathrm{e}^-,\mathrm{n}} \Big/ \left(\frac{dN_{\mathrm{n}}(\delta)}{dt}\right)_{\gamma,\mathrm{n}} \approx \frac{N_{\mathrm{e}}\left(\varepsilon \geq \varepsilon_{\mathrm{th,N}}(e^-, n)\right) \cdot v_{\mathrm{e}} \cdot < \sigma_{\mathrm{e}^-,\mathrm{n}}(\varepsilon_{\mathrm{e}}) >}{N_{\mathrm{e}} \cdot \frac{dN_\gamma(\delta)}{dt} \cdot \langle f_\gamma(\delta, \varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}))\rangle \cdot \sigma_{\mathrm{yield,N}} \cdot l_\gamma(\varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}), P)} \qquad (14)$$

In CINDA and ENDP libraries of the International Atomic Energy Agency only electrodisintegration cross sections of copper and uranium nuclei are available [60]: ${}^{63}_{29}\mathrm{Cu}(\mathrm{e}^-, \mathrm{n})\ {}^{63}_{29}\mathrm{Cu}$ $(= 0.0079–0.595$ mb in the 13.5–60 MeV range) [61] and ${}^{238}_{92}\mathrm{U}(\mathrm{e}^-, \mathrm{n})\ {}^{238}_{92}\mathrm{U}$ $(= 0.0465–2.993$ mb in the 7.78–60 MeV range) [62]. Most likely, these measured cross sections also include the channel $\gamma + p^+ \to n + e^+$ through the virtual photons. Because of the lack of data for nitrogen, we are forced to use the cross section for copper as closest to nitrogen. Letting $\sigma_{\mathrm{e}^-,\mathrm{n}} = 0.0079$ mb at the energy $\varepsilon_e = 13.5$ MeV, closest to the RREA average energy 6–7 MeV, we obtain $(\frac{dN_{\mathrm{n}}(\delta)}{dt})_{\mathrm{e}^-,\mathrm{n}}/(\frac{dN_{\mathrm{n}}(\delta)}{dt})_{\gamma,\mathrm{n}} \approx 10^{-4}$. Even with $\sigma_{\mathrm{e}^-,\mathrm{n}} = 0.18$ mb at $\varepsilon_e = 20$ MeV, the ratio is of 0.0016. The electrodisintegration $\sigma_{\mathrm{e}^-,\mathrm{n}}$ and photonuclear $\sigma_{\gamma,\mathrm{n}}$ cross sections are connected through the virtual photon spectrum $N_{\gamma,\mathrm{n}}(\varepsilon\omega)$: $\sigma_{\mathrm{e}^-,\mathrm{n}}(\varepsilon_{\mathrm{e}}) = \int_0^{\varepsilon_{\mathrm{e}}-m_{\mathrm{e}}} \sigma_{\gamma,\mathrm{n}}(\omega) \cdot N_{\gamma,\mathrm{n}}(\varepsilon, \omega Z, A)\frac{d\omega}{\omega}$. As $\sigma_{\gamma,\mathrm{n}}$ decreases with the atomic number, in nitrogen $\sigma_{\mathrm{e}^-,\mathrm{n}}$ is approximately 62/14 times less than in copper. So the deposition of the electrodisintegration to the total neutron yield is much less than that of photonuclear reactions. However, unlike the null yield of the nuclear fusion, the electrodisintegration yield is significant.

B. Inverse to the β-decay reaction $e^-(p^+, n)\nu_{\mathrm{e}}$

This reaction was attracted [63] to explain the extremely high yield of low-energy neutrons claimed to have been observed in correlation with lightning [7]. There is a significant difference between operational mechanisms of photonuclear and electrodisintegration reactions and the $e^-(p^+, n)\nu_{\mathrm{e}}$ reaction affecting their efficiency in the thunderstorm electric field. The thing is that, if after the bremsstrahlung or electrodisintegration interaction the remaining electron energy is above the runaway threshold [50,64,65], the electron is capable of proceeding to energize in the electric field and, as a consequence, of emitting high-energy bremsstrahlung and taking part in electrodisintegration reactions. On the contrary, the electron vanishes in the $e^-(p^+, n)\nu_{\mathrm{e}}$ reaction. In the thunderstorm atmosphere, this is a reaction with the hydrogen nucleus of the water:

$${}^{1}_{1}H + e^- + \varepsilon_e \to n + \nu_{\mathrm{e}} \qquad (15)$$

The threshold $\varepsilon_{\mathrm{th}}(\mathrm{e}^-, \mathrm{n})$ of this reaction, which is the boundary energy in the β-spectrum of the neutron decay [33,66]

$$e_{\mathrm{th}}(\mathrm{e}^-, \mathrm{n}) = (m_{\mathrm{n}} - m_{p+} - m_{e-}) \cdot c^2 = 0.783\ \mathrm{MeV}, \qquad (16)$$

is on the order of magnitude less than the average electron energy in RREA 6–7 MeV and the photonuclear threshold $\varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}) = 10.5$ MeV.

Besides, reactions of the same kind with nuclei of the main constituents of the atmosphere are feasible:

$${}^{14}_{7}N + e^- + \varepsilon_{\mathrm{e}} \to {}^{13}_{6}\mathrm{C} + n + \nu_{\mathrm{e}}; \qquad (17)$$

$${}^{16}_{8}\mathrm{O} + e^- + \varepsilon_{\mathrm{e}} \to {}^{15}_{7}\mathrm{N} + n + \nu_e. \qquad (18)$$

Their thresholds are the same as the thresholds of (10) and (11). As $\varepsilon_{\mathrm{th,N}}(\mathrm{e}^-, \mathrm{n}) = 10.5$ MeV is not too high than the average energy of electrons in RREA 6–7 MeV, a significant neutron yield can be expected.

The ratio of $e^-(p^+,\, n)\nu_\mathrm{e}$-to-($\gamma$, Xn) rates reads as follows:

$$\left(\frac{dN_\mathrm{n}(\delta)}{dt}\right)_{\mathrm{e}^-,\mathrm{n}} \Big/ \left(\frac{dN_\mathrm{n}(\delta)}{dt}\right)_{\gamma,\mathrm{n}} \approx \frac{N_\mathrm{e}(\varepsilon \geq \varepsilon_\mathrm{th}(\mathrm{e}^-,\mathrm{n}))\cdot \sigma_{\mathrm{e}^-,\mathrm{n}} \cdot v_\mathrm{e} \cdot [^1_1H]}{N_\mathrm{e}\cdot \frac{dN_\gamma}{dt} \cdot \langle f_\gamma(\delta, \varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n}))\rangle \cdot \sigma_{\mathrm{yield,N}} \cdot l_\gamma(\varepsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n})) \cdot [^{14}_7N]}. \tag{19}$$

For the reaction (17), $[^1_1H]$ is to be replaced by $[^{14}_7N]$.

As experimental data on the cross sections $\sigma_{\mathrm{e}^-,\mathrm{n}}$ of the reactions (15), (17), and (18) are not available, we estimate the $e^-(p^+,\, n)\nu_\mathrm{e}$ efficiency using the results of the analysis of "electroweak induced low-energy nuclear reactions" with "heavy" electron participation by Srivastava *et al.* [66]. The $e^-(p^+,\, n)\nu_\mathrm{e}$ cross section $\sigma_{\mathrm{e}^-,\mathrm{n}}$ describing neutron production in direct electron-proton collisions, derived in [66], is applicable to our case. Actually, since the cross section $\sigma_{\mathrm{e}^-,\mathrm{n}}$ in [66] diverges in the limit of small electron energies, it better fits the high-energy case than the case of heavy electron-proton interaction. The corresponding rate in $\hbar = c = 1$ units is as follows [66]:

$$v_\mathrm{e} \cdot \sigma_{\mathrm{e}^-,\mathrm{n}} \approx \frac{2G_\mathrm{F}^2}{\pi} \cdot \left(\tilde{m}_\mathrm{e} - \Delta\right)^2 \tag{20}$$

where $\tilde{m}_\mathrm{e}$ is the heavy electron mass, which we let be $\tilde{m}_\mathrm{e} = m_\mathrm{e} + \varepsilon_\mathrm{e}$; $\Delta = m_\mathrm{n} - m_{\mathrm{p}+}$; $G_F = 10^{-5}/M^2$ is Fermi's constant of the weak interaction and M is the nucleon mass. While converting $\sigma_{\mathrm{e}^-,\mathrm{n}}$ to natural units, the relation $200\ \mathrm{MeV} = 1/\mathrm{fermi}$ is convenient.

With the rate $\sigma_{\mathrm{e}^-,\mathrm{n}}(\varepsilon_\mathrm{e}) \cdot v_\mathrm{e} \sim 10^{-37}\ \mathrm{m}^3/\mathrm{s}$ evaluated letting $\varepsilon_\mathrm{e} \approx \epsilon_{\mathrm{th,N}}(\gamma, 1\mathrm{n})$ (i.e., $\tilde{m}_\mathrm{e} - \Delta \sim 10$ MeV), electron portions above the thresholds $N_\mathrm{e}(\varepsilon \geq \varepsilon_\mathrm{th}(\mathrm{e}^-,\mathrm{n}) = 0.783\ \mathrm{MeV})/N_\mathrm{e} \approx 0.81$ and $N_\mathrm{e}(\varepsilon \geq \varepsilon_\mathrm{th}(\mathrm{e}^-,\mathrm{n}) = 7.52\ \mathrm{MeV})/N_\mathrm{e} \approx 0.36$ computed using the RE distribution function [48], respectively, for the reactions (15) and (17), the concentration of hydrogen nuclei $[^1_1H] = 2[\mathrm{H_2O}] \approx 3.3\%$ [33], $[N_2] \approx 78\%$ and magnitudes of other quantities presented below Eq. (9); the ratio (19) is of 10^{-16} and 10^{-15}, respectively, for the reactions (15) and (17). So the $e^-(p^+,\, n)\nu_\mathrm{e}$ efficiency is insignificant compared to both the photonuclear and electrodisintegration reactions.

V. CONCLUSIONS

(1) The nuclear fusion is impossible in lightning channels because the electric field required for producing even one neutron in the channel is unreal: the required reduced strength is higher than $E/P \approx (55\text{–}174)\ \mathrm{MV}/(\mathrm{m}\cdot\mathrm{atm.})$. Such strong fields are generated only in small gas volumes using unique subnanosecond high-voltage generators. The acceleration (runaway) of deuterons "in the direction of the electron streaming" [32] in a strong electric field in hypothetical domains with violated quasineutrality is very unlikely because counterstreaming of a small portion of electrons prevents the quasineutrality violation. The eddy field that can be generated during neck instability of the lightning channel is too weak to accelerate deuterons up to the fusion energies.

(2) From numerous observations of γ-ray bursts with γ-spectra stretching above the threshold $\varepsilon_{\mathrm{th,N}}(\gamma, \mathrm{In})$ of photonuclear reactions (γ, Xn) and the results of numerical simulations, it follows that (γ, Xn) reactions do produce neutrons in a thunderstorm in numbers sufficient for detecting even at sea level. The doubts expressed in [7,15,32] about the capability of (γ, Xn) reactions to account for the neutron production in thunderstorm atmosphere are unwarranted. Most likely, photonuclear neutrons were generated both during execution neutron experiments [2–15] and experiments [4–6,8,17–23] in which γ-photons were observed with spectra above $\varepsilon_{\mathrm{th,N}}(\gamma, \mathrm{In})$. Results of the Aragats [4–6] experiment and numerical simulations [51–57] demonstrated that this can be the case in spite of the null result of the recent observations [67].

(3) Even if high-energy electrons are generated in lightning channels, the photonuclear reactions take their course outside them because ranges of γ-photons with energies above $\varepsilon_{\mathrm{th,N}}(\gamma, \mathrm{In})$ exceed transversal sizes of the channels. Hence, (γ, Xn) reactions are not capable of accounting for the neutron generation directly in the channels as sometimes is assumed [1,2,9–11,32].

(4) The neutron yields of electrodisintegration reactions, expected in a thunderstorm, are significant in contrast to the null yield of nuclear fusion. Nevertheless, they are less than predicted photonuclear yields.

(5) According to Larsen [63], the "…extraordinary high flux of low-energy neutrons" [7], claimed to have been observed in correlation with lightning discharges [7], is due to the $e^-(p^+,\, n)\nu_\mathrm{e}$ reaction. As was demonstrated by numerical simulations [6,24,25], a contribution of γ rays and, to a lesser degree, high-energy electrons dominated in count rates in [7]. Therefore, these rates cannot testify that neutrons were produced by the $e^-(p^+,\, n)\nu_\mathrm{e}$ reaction. Evaluations executed using the $e^-(p^+,\, n)\nu_\mathrm{e}$ cross section from [66] distinctly demonstrated that the $e^-(p^+,\, n)\nu_\mathrm{e}$ neutron yield is not significant.

(6) The strong interaction, by no means, can be responsible for the neutron generation by thunderstorms. The generation of neutrons in thunderstorms and thunderclouds appears to be connected with photonuclear reactions (γ, Xn) and, to a much lesser degree, with the electrodisintegration $^{14}_{7}\mathrm{N}(\mathrm{e}^-,\mathrm{n})^{13}_{7}\mathrm{N}$,

the relativistic runaway electron avalanches [27] being parent processes. New experiments are required to detect neutron flux increases correlated with thunderstorm activity. The key is to reliably and distinctly measure neutrons from other accompanied ionizing emissions.

ACKNOWLEDGMENTS

The VNIIEF coauthors express the deepest gratitude to Professor C. Haldoupis and Professor T. Neubert, the international collaborators on the completed ISTC Project No. 3993-2010, within the framework of which this work was carried out, to Dr. N. Crosby, Professor S. Cummer, Professor A. van Deursen, Professor J. R. Dwyer, Dr. R. Roussel-Dupré, Professor D. Smith, Dr. T. Torii, and Professor E. Williams for their support of the Project proposal. L. B. and I. K. thank Dr. R. A. Roussel-Dupré and Dr. E. M. D. Symbalisty for the long-term collaboration on the physics of atmospheric electricity, the continuation of which is this paper. H. R. expresses his sincere appreciation to Professor J. R. Dwyer for his guidance and suggestions during this work. Rassoul's contribution was supported in part by the DARPA Grant No. HR0011-1-10-1-0061.

[1] R. L. Fleisher, J. Geophys. Res. **80**, 5005 (1975).

[2] G. N. Shah, H. Razdan, G. L. Bhat, and G. M. Ali, Nature (London) **313**, 773 (1985).

[3] L. S. Bratolyubova-Tsulukidze, E. A. Grachev, O. R. Grigoryan, V. E. Kunitsyn, B. M. Kuzhevskij, D. S. Lysakov, O. Yu. Nechaev, and M. E. Usanova, Adv. Space Res. **34**, 1815 (2004).

[4] A. Chilingaryan, A. Daryan, K. Arakelyan, A. Hovhannisyan, B. Mailyan, L. Melkumyan, G. Hovsepyan, S. Chilingaryan, A. Reymers, and L. Vanyan, Phys. Rev. D **82**, 043009 (2010).

[5] A. Chilingaryan, N. Bostanjyan, and L. Vanyan, Phys. Rev. D **85**, 085017 (2012).

[6] A. Chilingarian, N. Bostanjyan, T. Karapetyan, and L. Vanyan, Phys. Rev. D **86**, 093017 (2012).

[7] A. V. Gurevich, V. P. Antonova, A. P. Chubenko *et al.*, Phys. Rev. Lett. **108**, 125001 (2012).

[8] H. Tsuchiya, K. Hibino, K. Kawata *et al.*Phys. Rev. D **85**, 092006 (2012).

[9] G. N. Shah, P. M. Ishtiaq, S. Mufti *et al.*, in *Proceedings of 30th Intern. Cosmic Ray Conference, Merida, Mexico*, 2007.

[10] A. N. Shyam and T. C. Kaushik, J. Geophys. Res. **104**, 6867 (1999).

[11] B. M. Kuzhewskiĭ, Bulletin of Moscow Lomonosov University Ser.: Phys. and Astronomy, **5**, 14 (2004).

[12] I. M. Martin and M. A. Alves. in *Proceedings of Chapman Conference on the Effects of Thunderstorms and Lightning in the Upper AtmospherePennsylvania, USA* 2009.

[13] I. M. Martin, M. A. Alves, G. I. Pugacheva, and A. Petrov, in Proceedings of 11th International Congress of the Brazilian Geophysical Society, Salvador, Brazil, 2009 (unpublished).

[14] I. M. Martin and M. A. Alves, J. Geophys. Res. **115**, A00E11 (2010).

[15] S. A. Starodubtsev, V. I. Kozlov, A. A. Toropov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **96**, 201 (2012) [JETP Lett.**96**, 188 (2012)].

[16] C. T. R. Wilson, Proc. Cambridge Philos. Soc. **22**, 534 (1925).

[17] H. Tsuchiya, T. Enoto, T. Torii *et al.*, Phys. Rev. Lett. **102**, 255003 (2009).

[18] H. Tsuchiya, T. Enoto, S. Yamada *et al.*, J. Geophys. Res. **116**, D09113 (2011).

[19] N. S. Khaerdinov, A. S. Lidvansky, and V. B. Petkov, Atmos. Res. **76**, 346 (2005).

[20] D. M. Smith, L. I. Lopez, R. P. Lin, and C. P. Barrington-Leigh, Science **307**, 1085 (2005).

[21] M. S. Briggs, G. J. Fishman, V. Connaughton *et al.*, J. Geophys. Res. **115**, A07323 (2010).

[22] M. Tavani *et al.*, Phys. Rev. Lett. **106**, 018501 (2011).

[23] H. Tsuchiya, T. Enoto, S. Yamada *et al.*, Phys. Rev. Lett. **99**, 165002 (2007).

[24] L. P. Babich, E. I. Bochkov, I. M. Kutsyk, and A. N. Zalyalov, Pis'ma Zh. Eksp. Teor. Fiz. **97**, 333 (2013) [JETP Lett. **97**, 291 (2013)].

[25] L. P. Babich, E. I. Bochkov, J. D. Dwyer, I. M. Kutsyk, and A. N. Zalyalov, J. Geophys. Res., Space Phys. **118**, 7905 (2013).

[26] L. B. Okun', in *Fizicheskaya Entsiklopediya [Physical Encyclopedia]*, edited by A. M. Prokhorov (Sov. Entsiklopediya, Moscow, 1994), Vol. 4.

[27] A. V. Gurevich, G. M. Milikh, and R. A. Roussel-Dupré, Phys. Lett. A **165**, 463 (1992).

[28] L. M. Libby and H. R. Lukens, J. Geophys. Res. **78**, 5902 (1973).

[29] L. P. Babich, Pis'ma Zh. Eksp. Teor. Fiz. **84**, 345 (2006) [JETP Lett. **84**, 285 (2006)].

[30] L. P. Babich, Geomagnetizm i Aeronomiya **47**, 702 (2007) [Geomagn. Aeron. **47**, 66 (2007)].

[31] L. P. Babich and R. A. Roussel-Dupré, J. Geophys. Res. **112**, D13303 (2007).

[32] T. Fülöp and M. Landreman, Phys. Rev. Lett. **111**, 015006 (2013).

[33] L. P. Babich, *High Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment and Natural phenomena* (FuturePast Inc., Arlington, 2003).

[34] *Physical Encyclopedia. Atmosphere*, edited by A. M. Prokhorov (Sov. Entsiklopediya, Moscow, 1988), Vol. 1.

[35] Yu. P. Raizer, *Gas Discharge Physics* (Springer, Berlin, 1991).

[36] E. M. Bazelyan and Yu. P. Raizer, *Lightning Physics and Lightning Protection* (IOP Publishing, Bristol, 2000).

[37] M. Uman, *The Lightning Discharge* (Dover, Mineola, 2001).

[38] V. A. Rakov and M. A. Uman, *Lightning Physics and Effects* (Cambridge University Press, Cambridge, 2003).

[39] *Tables of Physical Quantities*, edited by I. K. Kikoin (Atomizdat, Moscow, 1976).

[40] V. M. Bystritsky, V. V. Gerasimov, A. R. Krylov *et al.*, Nucl. Phys. **66**, 1731 (2003).

[41] M. I. Yalandin, S. K. Lyubutin, M. R. Oulmascoulov, S. N. Rukin, V. G. Shpak, S. A. Shunailov, and B. G. Slovikovsky, IEEE Trans. Plasma Sci. **30**, 1700 (2002).

[42] G. A. Mesyats and M. I. Yalandin Usp. Fiz. Nauk **175**, 225 (2005)[Phys. Usp. **48**, 211 (2005)].

[43] J. R. Dwyer, H. K. Rassoul, Z. Saleh, M. A. Uman, J. Jerauld, and J. A. Plumer, Geophys. Res. Lett. **32**, L01803 (2005).

[44] R. A. Marshall and U. S. Inan, Geophys. Res. Lett. **32**, L03813 (2005).

[45] D. J. Rose and M. Clark, Jr., *Plasmas and Controlled Fusion* (M.I.T. Press and J. Wiley & Sons, Inc., New York–London, 1963).

[46] A. J. Anderson and A. J. Eriksson, Electra **69**, 65 (1980).

[47] S. S. Dietrich and B. L. Berman, At. Data Nucl. Data Tables **38**, 199 (1988).

[48] L. P. Babich, E. N. Donskoy, R. I. Il'kaev, I. M. Kutsyk, and R. A. Roussel-Dupré, Fiz. Plazmy **30**, 666 (2004) [Plasma Phys. Rep. **30**, 616 (2004)].

[49] L. M. Coleman, and J. R. Dwyer, Geophys. Res. Lett. **33**, L11810 (2006).

[50] I. M. Kutsyk, L. P. Babich, E. N. Donskoi, and E. I. Bochkov, Pis'ma Zh. Eksp. Teor. Fiz. **95**, 712 (2012) [JETP Lett. **95**, 631 (2012)].

[51] L. P. Babich, A. Yu. Kudryavtsev, M. L. Kudryavtseva, and I. M. Kutsyk, Dokl. Akad. Nauk SSSR **415**, 394 (2007) [Dokl Earth Sci. **415**, 885 (2007)].

[52] L. P. Babich, A. Yu. Kudryavtsev, M. L. Kudryavtseva, and I. M. Kutsyk, Pis'ma Zh. Eksp. Teor. Fiz. **85**, 601 (2007) [JETP Lett. **85**, 483 (2007)].

[53] L. P. Babich, A. Yu. Kudryavtsev, M. L. Kudryavtseva, and I. M. Kutsyk, Zh. Eksp. Teor. Fiz. **133**, 80 (2008) [JETP **106**, 65 (2008)].

[54] L. P. Babich, E. I. Bochkov, I. M. Kutsyk, and R. A. Roussel-Dupré, J. Geophys. Res. **115**, A00E28 (2010).

[55] L. P. Babich, E. I. Bochkov, E. N. Donskoĭ, and I. M. Kutsyk, J. Geophys. Res. **115**, A09317 (2010).

[56] B. E. Carlson, N. G. Lehtinen, and U. S. Inan, J. Geophys. Res. **115**, A00E19 (2010).

[57] L. P. Babich, E. I. Bochkov, E. N. Donskoĭ, and I. M. Kutsyk, J. Geophys. Res. **115**, A09317 (2010).

[58] L. P. Babich, E. N. Donskoj, I. M. Kutsyk, and R. A. Roussel-Dupré, Geomagnetizm and Aeronomiya **44**, 697 (2004) [Geomagn. Aeron. **44**, 254 (2004)].

[59] *The Nuclear Handbook* edited by O. R. Frisch (George Newnes Limited, London, 1958).

[60] V. Zerkin, Experimental Nuclear Reaction Data (CINDA, ENDP), http://www-nds.iaea.org/exfor/exfor.htm.

[61] M. N. Martins, E. Hayward, G. Lamaze, X. Maruyama, F. Schima, and E. Wolynec, Phys. Rev. C **30**, 1855 (1984).

[62] F. Gerab and M. N. Martins, Phys. Rev. C **48**, 105 (1993).

[63] L. Larsen, http://www.slideshare.net/lewisglarsen/latticeenergyllc/new-russian-data-supports-wlt-neutron-production-in-lightning-april-4-2012.

[64] L. P. Babich, Teplofiz. Vys. Temp. **33**, 659 (1995) [High Temp. (USSR)**33**, 190 (1995)].

[65] I. M. Kutsyk, L. P. Babich, E. N. Donskoi, and E. I. Bochkov, Fiz. Plazmy **38**, 969 (2012) [Plasma Phys. Rep. **38**, 891 (2012)].

[66] Y. N. Srivastava, A. Widom, and L. Larsen, Pramana J. Phys. **75**, 617 (2010).

[67] V. Alexeenko, F. Arneodo, G. Bruno, W. Fulgione, D. Gromushkin, O. Shchegolev, Yu. Stenkin, V. Stepanov, V. Sulakov, V. Volchenko, and I. Yashin, in 33 International Cosmic Ray Conference, The Astroparticle Physics Conference, Rio de Janeiro, 2013 (unpublished).