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FUNDAMENTAL PROCESSES CAPABLE OF ACCOUNTING FOR THE NEUTRON FLUX ENHANCEMENTS IN A THUNDERSTORM ATMOSPHERE

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Elementary processes capable of producing neutrons in a thunderstorm atmosphere are analyzed. The efficiency of nuclear fusion $^2\mathrm{H}(^2\mathrm{H},n)^3\mathrm{He}$, photonuclear reactions (γ, Xn), electrodisintegration reactions $^n_m\mathrm{A}(e^-,n)^{n-1}_m\mathrm{A}$, and reactions $e^-(p^+,n)\nu_e$ opposite to the β-decay is evaluated. It is shown that an unrealistically strong electric field is required for the nuclear fusion to be responsible for the neutron production in the lightning channel. The generation of neutrons in a thunderstorm atmosphere is connected with photonuclear (γ, Xn) and, at a much lower degree, electrodisintegration reactions, the relativistic runaway electron avalanches being primary parent processes.

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1. INTRODUCTION

The paper by Shah et al. [1] communicating the first statistically significant amplifications of the neutron flux in the atmosphere correlated with lightning electromagnetic pulses was followed by a number of communications reporting thunderstorm-associated increases in count rates of neutron detectors located at satellites in near space [2], at high-mountain stations [3–8], and almost at sea level [9–14]. The increases could be considered a manifestation of nuclear reactions in thunderstorm electric fields predicted by Wilson long ago [15]. However, the neutron detectors used were gas-discharge counters based on reactions $^3\mathrm{He}(n,p)^3\mathrm{H}$ and $^{10}\mathrm{B}(n;^4\mathrm{He},\gamma)^7\mathrm{Li}$ [1–14]. In such counters, current pulses are excited by any ionizing radiation; therefore, they are sensitive not only to products of the above reactions (protons, tritons, alpha particles, and γ-photons). As demonstrated in [5, 16], most likely, with the exception of the Aragats experiment [3–5], in which high-energy electrons, γ-photons, and neutrons were being detected separately, results of other observations of neutron flux enhancements in a thunderstorm atmosphere are not trustworthy because a deposition of high-energy electrons, γ-rays, and positrons generated by thunderstorms could dominate.

Possibly, following the analysis by Libby and Lukens [17] and the communication by Fleisher, who first attempted to detect thunderstorm-related neutrons [18], the expected neutron generation in a thunderstorm atmosphere was conventionally connected with the nuclear fusion in lightning channels, first of all, with the $^2\mathrm{H}(^2\mathrm{H},n)^3\mathrm{He}$ reaction. But the kinetic energy of deuterons is limited by charge transfer reactions to such small magnitudes that the fusion yield in lightning channels is equal to zero even under the assumption of complete ionization of the deuterium in the damp atmosphere [19–21]. Because flashes of hard γ-rays not once were detected in correlation with thunderstorms, the photonuclear reactions (γ, Xn) are the most obvious elementary processes capable of accounting for the neutron production during thunderstorms [19–21]. Here, X is the neutron number in a particular photonuclear event.

The present analysis is motivated by the increasing number of communications on observations of the neutron flux amplification in a thunderstorm atmosphere [1–14] and the doubts [6, 14, 22] that these amplifications are due to photonuclear reactions. In the range of energies of $\sim$ 1 GeV (a reference point in high-energy physics), the characteristic times of strong (nuclear), electromagnetic, and weak interactions are

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respectively equal to $\tau_{str} \sim 10^{-24}$ s, $\tau_{el} \sim 10^{-21}$ s, and $\tau_{weak} \sim 10^{-10}$ s [23] and, at first glance, it seems that the strong interaction dominates, but we consider representatives of all fundamental interactions possibly occurring in a thunderstorm atmosphere. In our analysis, we reconsider possibilities of the nuclear fusion ^{2}H(^{2}H,n)^{3}He and photonuclear reactions initiated by relativistic runaway electron avalanches (RREA) [24]. For the first time, neutron-producing interactions of high-energy electrons with atomic nuclei are considered, which were not taken into account previously, though the observed pulses of hard γ-rays only are a secondary bremsstrahlung of high-energy electrons. The thresholds of some of the above reactions are lower than the threshold $\varepsilon_{th}(\gamma, 1n)$ of photonuclear reactions in air. Only this can make them more efficient than (γ, Xn) reactions in air. Furthermore, high-energy electrons directly produce neutrons, unlike photonuclear reactions requiring an intermediate bremsstrahlung process. Therefore, it is conceivable that the neutron yields due to interactions of high-energy electrons with atmospheric nuclei can be significant.

2. NUCLEAR FUSION

In this section, we reconsider the possibilities of nuclear fusion, but unlike in the previous analyses [19–21], where the neutron yield of the ^{2}H(^{2}H,n)^{3}He reaction was estimated in a lightning channel, we estimate the field strength required for producing at least one neutron in the channel. For this, as in [19–21], we proceed from the formula for the expected neutron yield of the reaction ^{2}H(^{2}H,n)^{3}He:

$$N_n \approx N_L P \cdot 2[\mathrm{H_2O}][\mathrm{D}] S_{ch} l_{ch} n_{ion} \Delta t \times \times \int\limits_{\varepsilon_{fus}}^{\infty} \upsilon_{ion}\sigma_{fus}(\varepsilon_{ion}) f(\varepsilon_{ion}, T)\, d\varepsilon_{ion}, \quad (1)$$

where $N_L \approx 2.7 \cdot 10^{25}$ m^{-3} · atm^{-1} is the number density of air molecules (Loshmidt's number), P [atm] is the pressure at the altitude of interest, [H$_2$O] and [D] are the relative concentration of water vapor molecules in a thunderstorm atmosphere and the relative concentration of deuterium atoms per hydrogen atom in natural water, ε_{ion}, υ_{ion}, and n_{ion} are the kinetic energy, velocity, and number density of the deuterium ions, S_{ch} and l_{ch} are the cross-sectional area and length of the lightning channel, Δt is the lifetime of the strong electric field within the lightning channel ($\upsilon_{ion}\Delta t \ll l_{ch}$), $\sigma_{fus}(\varepsilon_{ion})$ is the cross section for the nuclear fusion reaction, ε_{fus} is the minimum energy of deuterons below which nuclear fusion is inefficient, $f(\varepsilon_{ion}, T) = T^{-1}\exp(-\varepsilon_{ion}/T)$ is a nearly Maxwellian ion energy distribution function normalized to unity with the "temperature" $T = eE/N_L P\langle\sigma_t\rangle$ [19–21, 25], and $\langle\sigma_t\rangle$ is the averaged charge transfer cross section. The rate $\upsilon_{ion}\sigma_{fus}(\varepsilon_{fus})$ of the reaction ^{2}H(^{2}H,n)^{3}He is a weaker function of the ion energy ε_{ion} than $f(\varepsilon_{ion}, T)$, and therefore, after extracting the average rate of the fusion $\langle\upsilon_{ion}\sigma_{ion}(\varepsilon_{fus})\rangle$ from the integral in (1), the reduced field strength required for producing $N_n = 1$ can be estimated as

$$\frac{E}{P} \approx \varepsilon_{fus} N_L \langle\sigma_t\rangle \left\{\ln\left[N_L P \cdot 2[\mathrm{H_2O}][\mathrm{D}] n_{ion} S_{ch} l_{ch} \times \times \Delta t \langle\upsilon_{ion}\sigma_{fus}(\varepsilon_{fus})\rangle\right]\right\}^{-1}. \quad (2)$$

It is seen that the E/P magnitude weakly depends on the magnitudes of most quantities except ε_{fus} and $\langle\sigma_t\rangle$, the dependence on which is not too strong. In calculations, we use recognized, more or less realistic, literature magnitudes of the following quantities: according to a thickness of the "besieged water layer", we let [H$_2$O] $\approx$ 1.65 % (in tropics, [H$_2$O] $\approx$ 4 %) [26] and [D] = 0.015 % [26]; $S_{ch} \approx 3 \cdot 10^{-3}$ m^2 is the cross-sectional area of the hottest part of the channel through which the current is transported, $l_{ch} \approx$ 1–10 km, and $\Delta t \approx 50$ μs (typical length and duration of the return stroke) [27, 28]. The meanings of the other quantities in (2) are uncertain; therefore, we estimate E/P from below using meanings of these quantities that would give a strongly underestimated field strength. First, we let $n_{ion} = N_L P \cdot 2[\mathrm{H_2O}][\mathrm{D}]$. This is absolutely unrealistic condition assuming that all deuterium molecules in the entire volume of the channel $S_{ch} l_{ch} \approx$ 3–30 m^3 are dissociated and ionized, such that $2N_L P S_{ch} l_{ch} \approx 10^{26}$–$10^{27}$ deuterons participate in nuclear fusion at 1 atm. We also estimate the fusion rate $\langle\upsilon_{ion}\sigma_{fus}(\varepsilon_{fus})\rangle$ from above by letting $\sigma_{fus}(\varepsilon_{ion}) = \sigma_{fus,max} = 10^{-29}$ m^2 (ε_{ion} = 2–4 MeV) [29] and $\upsilon_{ion} \approx 2 \cdot 10^7$ m/s corresponding to these energies. On the contrary, we let $\varepsilon_{fus} = 1.7$ keV; with this energy, the ^{2}H(^{2}H,n)^{3}He cross section has the negligibly small value $\sigma_{fus} = 10^{-36}$ m^2 [30]. Because σ_t varies with ε_{ion} extremely weakly, it is sufficient to use any reasonable σ_t magnitude for $\langle\sigma_t\rangle$; we used σ_t = (4.25–12.5) · 10^{-20} m^2 [22] for the charge transfer reaction $\mathrm{D^+ + N_2 \to D + N_2^+}$ in the energy range above $\varepsilon_{fus} = 1.7$ keV (we note that $12.5 \cdot 10^{-20}$ m^2 is the σ_t maximum value achieved at 10 keV [22]). Even with these magnitudes, strongly underestimating E/P, we obtain that for producing only one neutron, the field is required with the strength $E/P >$ (55–174) MV/(m·atm), exceeding not only the strength 3 MV/(m·atm) required for self-breakdown in a homogeneous field [27, 28], but even the strength of the fields generated in small gaps of centimeter range with the use of high-voltage pulses of hundreds kilovolt with subnanosecond or even picosecond rise times allowing preventing the conventional breakdown and rapid collapse of the voltage (cf., e. g., [25, 31] and the references therein). The above estimation, being very conservative relative to all parameters, confirms that nuclear fusion is absolutely impossible in relatively slow process of lightning discharge in such a dense medium as lower layers of the atmosphere.

3. PHOTONUCLEAR REACTIONS

The threshold energies of photonuclear reactions $\gamma(^{14}\mathrm{N}, 1n)^{13}\mathrm{N}$ and $\gamma(^{16}\mathrm{O}, 1n)^{15}\mathrm{O}$ with the nuclei of the main atmospheric components are equal to $\varepsilon_{th,\mathrm{N}}(\gamma, 1n) = 10.55$ MeV and $\varepsilon_{th,\mathrm{O}}(\gamma, 1n) = 15.7$ MeV [32]. Significantly, the average energy of electrons in the RREA of 6–7 MeV [33–35] for the field overvoltages, conventionally defined relative to the minimum of the electron drag force in air

$$\delta = \frac{eE}{F_{min}P} = \frac{eE/P}{218\ \mathrm{keV}/(\mathrm{m}\cdot\mathrm{atm})},$$

below the self-breakdown limit $\delta \approx 14$, is not too much less than $\varepsilon_{th,\mathrm{N}}(\gamma, 1n)$. The authors of [6], while substantiating their doubts concerning the capability of (γ, Xn) reactions to account for the neutron flux amplifications in a thunderstorm atmosphere, wrote that at "...high energies 10–30 MeV the only work where the flux of the γ-ray emission during thunderstorms was measured from the ground is [3]". However, there are numerous well-known experiments, not only [3], in which γ-spectra of a thunderstorm origin were measured extending to energies ε_γ close to or much higher than $\varepsilon_{th,\mathrm{N}}(\gamma, 1n)$: 40–50 MeV [3], above 40 MeV [7], 10 MeV [36, 37], and above 10 MeV [38], measured respectively at altitudes 3250 m [3], 4300 m [7], 2770 m [36, 37], and 1700 m [38]; above 20 MeV [39], 30–38 MeV [40], and 100 MeV [41] measured in near space; up to ~ 35 MeV with small and up to ~ 70 MeV with large errors at sea level [37, 42]. We note that the γ-fluxes in their sources are more intensive and their spectra are 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 accounting for the neutron generation in a thunderstorm atmosphere.

Following this idea, yields of (γ, Xn) reactions from thunderstorms not once have been calculated (cf. [43–46] and the references therein). However, in view of the doubts in [6, 14, 22] and to demonstrate the capabilities of photonuclear reactions, we have analyzed, as the most illuminating case, a possibility of generation of photonuclear neutrons by prolonged (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 γ-ray spectrum and the fluence $F_\gamma^{exp} \approx 2 \cdot 10^4$ 1/m^2 were measured [37, 42]. Because absolute numbers of γ-photons and γ-spectrum in the source, not at the detector, are required in performing Monte Carlo simulations [16, 45], we have used the universal bremsstrahlung spectrum of the RREA [47] for the γ-ray source. With this emission spectrum of the γ-ray source, located at altitudes $z_\gamma^{emis} \le 2$ km, the calculated γ-spectrum at sea level [45] excellently agrees with the measured γ-spectrum [37, 42]. Simulating transport of γ-photons by the Monte Carlo technique down to sea level with subsequent fitting to the measured γ-ray fluence F_γ^{exp}, we calculated absolute numbers of γ-photons emitted by the source located at altitudes $z_\gamma^{emis} = 1$–10 km to be $N_{\gamma,emis} = 6.8 \cdot 10^{13}$–$2.8 \cdot 10^{20}$. The required numbers of high-energy electrons N_e imposed by the relativistic feedback [48, 49] are of the same order of magnitude as the $N_{\gamma,emis}$ numbers. We calculated the numbers of γ-photons above the threshold $\varepsilon_{th,\mathrm{N}}(\gamma, 1n)$ by multiplying $N_{\gamma,emis}$ by the fraction of γ-photons above the threshold in the RREA bremsstrahlung spectrum [47],

$$\Delta_\gamma(\delta, \varepsilon_{th,\mathrm{N}}(\gamma, 1n)) = \int\limits_{\varepsilon_{th,\mathrm{N}}(\gamma,1n)}^{\infty} f_\gamma(\delta, \varepsilon_\gamma)\, d\varepsilon_\gamma, \qquad (3)$$

where $f_\gamma(\delta, \varepsilon_\gamma)$ is the photon distribution function normalized to unity [47]. Calculated at sea level fluence $\sim 10^3$–10^4 n/m^2 [16, 45] of photonuclear neutrons generated by these γ-rays while their transport in atmosphere, is sufficient for registration. Actually, if the communication in [1] about the events with detected numbers of neutrons $N_{det} = 3$–60 in the high-mountainous (~ 3 km) experiment is trustworthy, a lower fluence of (34–670) n/m^2 corresponds to these N_{det} magnitudes.

4. ELECTRON-INDUCED NUCLEAR REACTIONS

As pointed out above, the high-energy electrons directly produce neutrons, and therefore their neutron yields can be expected to be higher than the photonuclear yield. To evaluate neutron yields due to interactions of high-energy electrons with atmospheric nuclei, the high-energy electron numbers N_e must be known. These numbers have been estimated to fit the observational data of various high-energy phenomena (see, e. g. [16, 43–46, 50–52] and the references therein). To avoid using N_e directly, we compare neutron yields of electron–induced nuclear reactions with those of photonuclear reactions and thus clarify the relative efficiency of electron–nuclear interactions. We consistently adopt the theoretical approach using only recognized computed characteristics of RREA and its bremsstrahlung combined with available nuclear data. Within the accuracy of the present analysis, it is sufficient only to allow for interactions with $^{14}_{7}$N nuclei, because concentrations of other air components are small in comparison with nitrogen concentration $[\mathrm{N_2}]$ and their thresholds are much larger than $\varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.55$ MeV.

The rate of the photonuclear generation of neutrons can be estimated as the number of neutrons produced per unit time along the γ-ray range l_γ:

$$\left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} = N_e\frac{dN_\gamma(\delta)}{dt}\cdot 2N_L P[\mathrm{N_2}]\times$$
$$\times\int\limits_{\varepsilon_{th,\mathrm{N}}(\gamma,1n)}^{\infty} f_\gamma(\delta,\varepsilon_\gamma)\sigma(\gamma,Xn)l_\gamma(\varepsilon_\gamma)\,d\varepsilon_\gamma \approx$$
$$\approx N_e\frac{dN_\gamma(\delta)}{dt}\langle f_\gamma(\delta,\varepsilon_{th,\mathrm{N}}(\gamma,1n))\rangle\cdot 2N_L P[\mathrm{N_2}]\times$$
$$\times\,\sigma_{yield}(\varepsilon_{th,\mathrm{N}}(\gamma,1n))l_\gamma(\varepsilon_{th,\mathrm{N}}(\gamma,1n),P), \quad (4)$$

where N_e is the total number of REs (runaway electrons) at the overvoltage δ, $dN_\gamma(\delta)/dt$ is the rate of photon emission per one RE,

$$\sigma(\gamma,Xn) = \sum_i i\sigma(\gamma,in) + \nu\sigma(\gamma,f),$$

$\sigma(\gamma,in)$ is the cross section of the reaction (γ,in) with a yield of i neutrons, $\sigma(\gamma,f)$ is the photonuclear fission cross section with a yield of ν neutrons,

$$\sigma_{yield}(\varepsilon_{\gamma,max}) =$$
$$= \int\limits_{\varepsilon_{th}(\gamma,1n)}^{\varepsilon_{\gamma,max}} \sigma(\gamma,Xn)\,d\varepsilon \approx 98.8\cdot 10^{-31}\ \mathrm{MeV\cdot m^2}$$

is the total photoneutron yield cross section [32], $\varepsilon_{\gamma,max}\approx 29.5$ MeV is a maximal energy at which data on the cross section $\sigma(\gamma,Xn)$ are available in [32], and $l_\gamma(\varepsilon_{th,\mathrm{N}},P)$ is the range of photons with the energy $\varepsilon_{th,\mathrm{N}}$ at the pressure P. We use

$$\langle f_\gamma(\delta,\varepsilon_{th})\rangle > \frac{1}{\varepsilon_{\gamma,max}-\varepsilon_{th}(\gamma,n)}\times$$
$$\times\int\limits_{\varepsilon_{th}(\gamma,n)}^{\varepsilon_{\gamma,max}} f_\gamma(\delta,\varepsilon_\gamma)\,d\varepsilon_\gamma \approx 5\cdot 10^{-4}\ \frac{1}{\mathrm{MeV}}$$

and

$$\frac{dN_\gamma(\delta)}{dt}\approx 10^7\ \frac{1}{\mathrm{s\cdot atm\cdot RE}}$$

computed for the RREA in air [47], and $l_\gamma(\varepsilon_{th,\mathrm{N}}, P = 1\ \mathrm{atm})\approx 500$ m [26]. Reactions of electrodisintegration and reactions $e^-(p^+,n)\nu_e$ opposite to the β-decay are considered.

5. ELECTRODISINTEGRATION REACTIONS $^{n}_{m}\mathbf{A}(e^-,n)^{n-1}_{m}\mathbf{A}$

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

$$^{14}_{7}\mathrm{N} + e^- + \varepsilon_e \to {}^{13}_{7}\mathrm{N} + n + e^-, \quad (5)$$
$$^{16}_{8}\mathrm{O} + e^- + \varepsilon_e \to {}^{15}_{8}\mathrm{O} + n + e^-, \quad (6)$$

where ε_e is the kinetic energy of the incident electron. Their thresholds can be calculated as the mass defect using nuclei masses available in handbook [53] or elsewhere:

$$\varepsilon_{th,\mathrm{N}}(e^-,n) = \left(M(^{13}_{7}\mathrm{N}) + m_n - M(^{14}_{7}\mathrm{N})\right)c^2 =$$
$$=10.55\ \mathrm{Mev}\quad \cancel{= 7.52\ \mathrm{MeV}.} \quad (7)$$

$$\varepsilon_{th,\mathrm{O}}(e^-,n) = \left(M(^{15}_{8}\mathrm{O}) + m_n - M(^{16}_{8}\mathrm{O})\right)c^2 =$$
$$=15.7\ \mathrm{MeV}\quad \cancel{= 12.09\ \mathrm{MeV}.} \quad (8)$$

The photonuclear threshold $\varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.5$ MeV in nitrogen ~~exceeds the~~ is the same as threshold in (7), ~~which is~~ both are rather close to the average energy of electrons, 6–7 MeV, in the RREA.

The rate of the electrodisintegration of nitrogen nuclei can be estimated as

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} = N_e\cdot 2N_L P[\mathrm{N_2}]\times$$
$$\times\int\limits_{\varepsilon_{th,\mathrm{N}}(e^-,n)}^{\infty} f_e(\delta,\varepsilon_e)\sigma_{e^-,n}(\varepsilon_e)v_e d\varepsilon_e \approx$$
$$\approx N_e\left(\varepsilon\ge\varepsilon_{th,\mathrm{N}}(e^-,n)\right)v_e\langle\sigma_{e^-,n}\rangle\cdot 2N_L P[\mathrm{N_2}], \quad (9)$$

where

$$N_e\left(\varepsilon\ge\varepsilon_{th,\mathrm{N}}(e^-,n)\right) =$$
$$= N_e\int\limits_{\varepsilon_{th,\mathrm{N}}(e^-,n)}^{\infty} d\varepsilon_e f_e(\delta,\varepsilon_e)\approx 0.36N_e$$

is the RE number above the electrodisintegration threshold $\varepsilon_{th,\mathrm{N}}(e^-,n)$, $f_e(\delta,\varepsilon_e)$ is the RE universal distribution function, which is almost independent of δ [33], and $\upsilon_e \approx 2.7\cdot 10^8$ m/s is the RE velocity [34, 35].

The (9)-to-(4) ratio is

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} \Bigg/ \left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} \approx \frac{N_e\left(\varepsilon \ge \varepsilon_{th,\mathrm{N}}(e^-,n)\right)\upsilon_e\langle\sigma_{e^-,n}(\varepsilon_e)\rangle}{N_e\dfrac{dN_\gamma(\delta)}{dt}\langle f_\gamma(\delta,\varepsilon_{th,\mathrm{N}}(\gamma,1n))\rangle\sigma_{yield,\mathrm{N}}l_\gamma(\varepsilon_{th,\mathrm{N}}(\gamma,1n),P)}. \qquad (10)$$

To the author's knowledge, the cross sections $\sigma_{e^-,n}(\varepsilon_e)$ of reactions (5) and (6) are absent. Only cross sections of three electrodisintegration reactions are available in CINDA and ENDP libraries of the International Agency for Atomic Energy [54]: ${}^{63}_{29}\mathrm{Cu}(e^-,n){}^{62}_{29}\mathrm{Cu}$ ($\sigma_{e^-,n} = 0.0079$–0.595 mb in the 13.5–60 MeV range) [55], ${}^{63}_{29}\mathrm{Cu}(e^-,2n){}^{61}_{29}\mathrm{Cu}$ ($\sigma_{e^-,2n} = 0.0224$–0.085 mb in the 28–60 MeV range) [56], and ${}^{238}_{92}\mathrm{U}(e^-,n){}^{237}_{92}\mathrm{U}$ ($\sigma_{e^-,n} = 0.0465$–2.993 mb in the 7.78–60 MeV range) [57]. Therefore, we are forced to use the ${}^{63}_{29}\mathrm{Cu}(e^-,n){}^{62}_{29}\mathrm{Cu}$ cross section for $\langle\sigma_{e^-,n}\rangle$, because the copper nucleus is the closest to the nitrogen nucleus. Other cross sections are quoted to demonstrate the order of magnitudes of this quantity for different nuclei. Letting $\sigma_{e^-,n} = 0.0079$ mb at $\varepsilon_e = 13.5$ MeV (the energy closest to the RREA average energy 6–7 MeV), we obtain

0.0001

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} \Bigg/ \left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} \approx \cancel{0.004}.$$

Even with $\sigma_{e^-,n} = 0.18$ mb at $\varepsilon_e = 20$ MeV, the ratio is

0.0016

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} \Bigg/ \left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} \approx \cancel{0.07}.$$

The electrodisintegration $\sigma_{e^-,n}$ and photonuclear $\sigma_{\gamma,n}$ cross sections are connected via the virtual photon spectrum $N_{\gamma,n}(\varepsilon,\omega)$:

$$\sigma_{e^-,n}(\varepsilon_e) = \int\limits_0^{\varepsilon_e - m_e} \sigma_{\gamma,n}(\omega)N_{\gamma,n}(\varepsilon,\omega,Z,A)\frac{d\omega}{\omega}.$$

Because $\sigma_{\gamma,n}$ decreases with the atomic number, $\sigma_{e^-,n}$ is approximately 62/14 times less in nitrogen than in copper. Hence, the deposition of the electrodisintegration to the total neutron yield is much less than that of photonuclear reactions, but unlike the null yield of nuclear fusion, the electrodisintegration yield can be significant.

6. WEAK REACTIONS $e^-(p^+,n)\nu_e$ OPPOSITE TO THE β-DECAY

In a thunderstorm atmosphere, these are reactions with hydrogen nuclei of the water vapor:

$${}^1_1\mathrm{H} + e^- + \varepsilon_e \to n + \nu_e. \qquad (11)$$

The threshold energy $\varepsilon_{th}(e^-,n)$ of this reaction, which is actually the boundary energy in the electron spectrum of the neutron β-decay [23, 58],

$$\varepsilon_{th}(e^-,n) = (m_n - m_{p^+} - m_{e^-})c^2 = 0.783 \text{ MeV} \qquad (12)$$

is more than an order of magnitude less than $\varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.5$ MeV. Besides, reactions of the same kind with the nuclei of the main constituents of the atmosphere are feasible:

$${}^{14}_7\mathrm{N} + e^- + \varepsilon_e \to {}^{13}_6\mathrm{C} + n + \nu_e, \qquad (13)$$

$${}^{16}_8\mathrm{O} + e^- + \varepsilon_e \to {}^{15}_7\mathrm{N} + n + \nu_e. \qquad (14)$$

Naturally, their thresholds

$$\varepsilon_{th}(e^-,n) = \left(M({}^{13}_6\mathrm{C}) - M({}^{14}_7\mathrm{N}) + m_n - m_e\right)c^2 = 7.52 \text{ MeV} \qquad (15)$$

and

$$\varepsilon_{th}(e^-,n) = \left(M({}^{15}_6\mathrm{N}) - M({}^{16}_8\mathrm{O}) + m_n - m_e\right)c^2 = 12.09 \text{ MeV}, \qquad (16)$$

are the same as (7) and (8) and much higher than threshold (12) of reaction (11), but threshold (15) of the reaction with nitrogen, the main component of air, is less than $\varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.5$ MeV and rather close to the average energy of electrons in the RREA, 6–7 MeV [33–35]. Therefore significant neutron yields can be expected.

It is worth noting that if the energy remaining after the bremsstrahlung emission and electrodisintegration reaction is above the runaway threshold [25, 59, 60], then the electron is capable of proceeding energizing in the electric field and, as a consequence, capable of emitting high-energy bremsstrahlung and taking part in electrodisintegration reactions. Unlike the cases of the bremsstrahlung process and electrodisintegration reaction, the electron vanishes in the $e^-(p^+,n)\nu_e$ reactions. Hence, the $e^-(p^+,n)\nu_e$ yields can by no means exceed the initial number of high-energy electrons $N_e(\varepsilon_e > \varepsilon_{th}(e^-,n))$ above thresholds (12), (15), and (16). Actually, the yields should be many orders of magnitude less than $N_e(\varepsilon_e > \varepsilon_{th}(e^-,n))$.

To our knowledge, experimental data on the cross sections of reactions (11), (13), and (14) are absent. However, there is a possibility to carry out estimations of the efficiency of the reaction $e^-(p^+,n)\nu_e$ using data of the theoretical analyses with participation of "heavy" electron [58]. First, we use "... an order of the magnitude estimate of the rate of this reaction ..." carried out on dimensional grounds in [58]:

$$\Gamma\left(e^-(p^+,n)\nu_e\right) \approx \frac{G_F^2 m_e^5 c^4}{\hbar^7}\left(\frac{\tilde{m}_e-\Delta}{\Delta}\right)^2 \approx \approx 7\cdot 10^{-3}\left(\frac{\tilde{m}_e-\Delta}{\Delta}\right)^2 \frac{1}{\mathrm{s}}, \quad (17)$$

where $G_F \approx 0.875\cdot 10^{-37}$ eV$\cdot$cm^3 is the weak interaction constant (Fermi's constant), $\Delta = m_n - m_{p^+}$, and $\tilde{m}_e$ is a mass of the "heavy" electron, which in the framework of the problem considered we let to be $\tilde{m}_e = m_e + \varepsilon_e$ in energy units. Actually, the rate in (17) is very close to that of free neutron β-decay [23], because the factor $G_F^2 m_e^5 c^4/\hbar^7$ dominates. Even with not too high an electron energy, e. g., $\varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.5$ MeV, the rate in (17) is equal to 0.39 1/s. With the concentration of hydrogen nuclei (protons) $[^1_1\mathrm{H}] = 2[\mathrm{H_2O}] \approx 3.3\,\%$ (cf., Sec. 2), this rate, being used directly, gives the unrealistic $e^-(p^+,n)\nu_e$-to-(γ,Xn) rate ratio

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} \Big/ \left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} \approx 5\cdot 10^{20}, \quad (18)$$

meaning that the $e^-(p^+,n)\nu_e$ reaction dominates. If ratio (18) were valid, not only the neutron yields but also the detected neutron numbers would be enormous, in contradiction to the observed count rates [1–14]. With the computed lowest number of high-energy electrons $N_e = 6.8\cdot 10^{13}$ required for producing bremsstrahlung at the altitude $z_\gamma^{emis} = 1$ km and capable of fitting the data on γ-ray flashes in [37, 42] (cf. Sec. 3), the specific rate at 1 atm

$$N_e\Gamma(e^-(p^+,n)\nu_e)\cdot 2N_L P[^1_1\mathrm{H}] \approx 0.5\cdot 10^{38}\ \frac{1}{\mathrm{m^3\cdot s}}$$

is by many orders of magnitude greater than the production rate of neutrons in nuclear explosion, for instance, according to the data in [61].

Obviously, directly using formula (17) is not appropriate. We observe, however, that both in the β-decay and in the "electroweak-induced low-energy nuclear reactions" in [58], parent unstable system exists, i. e., a β-unstable nucleus in the first case and "a heavy electron–proton pair" [58] in the second. Therefore, using formula (17) requires knowledge of the rate of parent electron–proton pair production $\sigma_{e,p}\upsilon_e$, with which the ratio similar to (10) is given by

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} \Big/ \left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} \approx \frac{N_e\left(\varepsilon \ge \varepsilon_{th}(e^-,n)\right)\sigma_{e,p}\upsilon_e[^1_1\mathrm{H}]\Gamma\left(e^-(p^+,n)\nu_e\right)}{N_e\dfrac{dN_\gamma}{dt}\langle f_\gamma(\delta,\varepsilon_{th,\mathrm{N}}(\gamma,1n))\rangle\sigma_{yield,\mathrm{N}}c[^{14}_7\mathrm{N}]}, \quad (19)$$

where chaotic motion of γ-rays is assumed as more appropriate. The cross section $\sigma_{e,p}$ can be roughly estimated using the proton "gas-kinetic cross section" $\pi r_{p^+}^2$, where $r_{p^+} \approx 10^{-15}$ m is the proton radius, i. e., the size of the space where the charge is concentrated. With the hydrogen and nitrogen concentrations $[^1_1\mathrm{H}] = 2[\mathrm{H_2O}] \approx 3.3\,\%$ and $[^{14}_7\mathrm{N}] \approx 75\,\%$, letting the electron energy be $\varepsilon_e = \varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.5$ MeV and using $N_e(\varepsilon \ge 0.783\ \mathrm{MeV})/N_e \approx 0.81$ according to the RREA electron distribution [33], this ratio for reaction (11) is of the order 10^{-6}. The magnitudes of other quantities in the denominator are given below Eq. (10). For reaction (13), after replacing $[^1_1\mathrm{H}]$ with $[^{14}_7\mathrm{N}]$ and using $N_e(\varepsilon \ge 7.52\ \mathrm{MeV})/N_e \approx 0.36$ [33], the ratio (19) is of the order 10^{-5}. Obviously, varying the cross section $\sigma_{e,p}$ of the parent high-energy electron–proton pair production within a rather large range does not change the conclusion that with the rate $\Gamma\left(e^-(p^+,n)\nu_e\right)$, the yield of the $e^-(p^+,n)\nu_e$ reactions is significantly less than the photonuclear yield.

To confirm that according to (17) the rate is proportional to $(\tilde{m}_e-\Delta)^2$, a formula for the rate of "heavy"-electron–proton interaction in $\hbar = c = 1$ units was derived in [58]:

$$\upsilon_e\sigma_{e^-,n} \approx \frac{2G_F^2}{\pi}\left(\tilde{m}_e-\Delta\right)^2, \quad (20)$$

where in these units, $\sigma_{e^-,n}$ is the $e^-(p^+,n)\nu_e$ cross section, $G_F = 10^{-5}/M^2$ [62], and M is the nucleon mass. The derivation of this cross section did not assume the existence of a parent unstable system; $\sigma_{e^-,n}$ describes neutron production in direct electron–proton collision [58]. Then the $e^-(p^+,n)\nu_e$-to-(γ,Xn) ratio is given by

$$\left(\frac{dN_n(\delta)}{dt}\right)_{e^-,n} \Big/ \left(\frac{dN_n(\delta)}{dt}\right)_{\gamma,n} \approx \frac{N_e\left(\varepsilon \ge \varepsilon_{th}(e^-,n)\right)\sigma_{e^-,n}v_e[{}^1_1\mathrm{H}]}{N_e\dfrac{dN_\gamma}{dt}\langle f_\gamma(\delta,\varepsilon_{th,\mathrm{N}}(\gamma,1n))\rangle\sigma_{yield,\mathrm{N}}l_\gamma\left(\varepsilon_{th,\mathrm{N}}(\gamma,1n)\right)[{}^{14}_7\mathrm{N}]}. \tag{21}$$

In converting the cross section $\sigma_{e^-,n}$ to the natural units (m^2 or barns), it is necessary, using $G_F \approx \approx 0.875\cdot 10^{-37}$ eV·cm^3, to divide $\sigma_{e^-,n}$ by $\hbar^4c^4$. It is more convenient to use the known relation 200 MeV = = 1/fermi, where 1 fermi = 10^{-13} cm. With the rate $\sigma_{e^-,n}(\varepsilon_e)v_e \sim 10^{-37}$ m^3/s evaluated, letting $\tilde{m}_e - \Delta = m_e + \varepsilon_e - \Delta \sim 10$ MeV ($\varepsilon_e \approx \varepsilon_{th,\mathrm{N}}(\gamma,1n)) \approx \approx 10.5$ MeV), and taking the magnitudes of other quantities to be those below Eqs. (10) and (19), the ratio (21) is of the order 10^{-16} and 10^{-15} for respective reactions (11) and (13). In evaluating the ratio for reaction (13), the hydrogen concentration $[{}^1_1\mathrm{H}]$ is replaced by $[{}^{14}_7\mathrm{N}]$. Hence, the $e^-(p^+,n)\nu_e$ efficiency is insignificant in comparison with the efficiency of photonuclear reactions (γ,Xn).

7. CONCLUSIONS

1. We confirmed the conclusion in (19)–(21) that nuclear fusion is impossible in lightning discharges because the electric field required for producing at least one neutron in the lightning channel with fully ionized deuterium is unrealistic: the required reduced strength is higher than $E/P \approx$ (55–174) MV/(m·atm). Such strong fields can be generated using unique high-voltage technology, only under laboratory conditions and only in small air volumes.

2. It follows from numerous observations of γ-ray bursts with γ-spectra stretching above the threshold $\varepsilon_{th}(\gamma,1n) = 10.5$ MeV of neutron-producing photonuclear reactions (γ,Xn) and from our numerical simulations that (γ,Xn) reactions do produce neutrons in a thunderstorm atmosphere in numbers capable of fitting the detected neutron numbers. The doubts in [6, 14, 22] regarding the capability of (γ,Xn) reactions to produce neutrons in a thunderstorm atmosphere are groundless, especially because the threshold $\varepsilon_{th,\mathrm{N}}(\gamma,1n) = 10.55$ MeV in nitrogen is not too far from the average energy 6–7 MeV of electrons in the relativistic runaway electron avalanche accounting for runaway breakdown [24]. Most likely, photonuclear neutrons were generated both in the neutron experiments in [1–14] and in experiments in [3–5, 7, 36–42], in which γ-photons were observed with spectra above $\varepsilon_{th,\mathrm{N}}(\gamma,1n)$. The problem is to reliably select neutrons from other thunderstorm-related penetrating emissions.

3. Whether high-energy electrons emitting bremsstrahlung in the γ-range are generated in contracted lightning channels or in volumetric high-altitude discharges (cf. [19–21, 44–46] and the references therein) similar to volumetric discharges intended for pumping gas lasers with external preionization [63], the photonuclear reactions take their course outside the channels, because ranges of γ-photons with energies above $\varepsilon_{th,\mathrm{N}}(\gamma,1n)$, being of the order of hundreds of meters, exceed the transverse sizes of the hottest domains of lightning channels, which are ~ 0.1 m [27, 28]. Therefore, (γ,Xn) reactions do not account for the neutron generation directly in the channels, as was assumed in [1, 8–10, 17, 18]. This assertion can also be advocated by the fact that the 1 min duration of the γ-ray bursts detected in [3–5, 7, 36, 37, 42] is much longer than that of the average return stroke (~ 50 μs [27, 28]). Tsuchiya et al. mention that the γ-bursts were not correlated with the lightning optical flash. Also it is pertinent to note that prolonged generation of x-rays in thunderclouds observed in [64] was abruptly "switched off" by lightning discharges. Possibly, the high-energy processes responsible for the prolonged generation of penetrating emissions by thunderstorm electric fields are not connected with lightning.

4. The neutron yields of electrodisintegration reactions expected in a thunderstorm atmosphere are significant in contrast to the null yield of nuclear fusion, but it is nevertheless much smaller than the yield of photonuclear reactions.

5. According to [65], the "... extraordinary high flux of low-energy neutrons generated during thunderstorms ...", which was claimed to be observed in correlation with lightning discharges [6], is due to the $e^-(p^+,n)\nu_e$ reaction, opposite to the neutron β-decay. As was demonstrated by numerical simulations [5, 16], the contribution of γ-rays and high-energy electrons

dominated in count rates in [6]. Therefore, the data in [6] cannot be an argument in favor of the idea that neutrons in thunderstorms were produced by the $e^-(p^+,n)\nu_e$ reaction. Evaluations performed with the use of the $e^-(p^+,n)\nu_e$ cross section derived in [58] demonstrated that the $e^-(p^+,n)\nu_e$ neutron yield is insignificant.

6. Thus, we confirmed that strong interaction can by no means be responsible for neutron generation by the thunderstorm electric field. The generation of neutrons in thunderstorms and thunderclouds is connected with photonuclear reactions (γ, Xn) and, at a much less degree, with electrodisintegration reactions ${}^{14}_{7}\mathrm{N}(e^-,n){}^{13}_{7}\mathrm{N}$, the relativistic runaway electron avalanches [24] being parent processes for both.

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