Analysis of a laboratory experiment on neutron generation by discharges in the open atmosphere

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A recently reported laboratory experiment with a high-voltage long discharge in the open atmosphere producing neutrons "...up to energies above 10 MeV..." [Agafonov *et al.*, Phys. Rev. Lett. **111**, 115003 (2013)] is critically analyzed. Known elementary processes, namely, nuclear synthesis $^2H(^2H,n)\ ^3He$ and $^2H(^{14}N,n)\ ^{15}O$, photonuclear, electrodisintegration $^n_mA(e^-,n)\ ^{n-1}_{m}A$ and opposite to the β-decay $e^-(p^+,n)\nu_e$ reactions, as well as unconventional mechanisms and the hypothetical increase in the nuclear synthesis cross sections are not capable of accounting for the neutron generation under conditions of the experiment analyzed. In particular, total energy yields of reactions $^2H(^2H,n)\ ^3He$ and $^2H(^{14}N,n)\ ^{15}O$ are less than the claimed neutron energy above 10 MeV. Trustworthiness of the neutron measurements on the basis of the available study of the C-39 track detectors behavior carried out by Faccini *et al.* [Eur. Phys. J. C **74**, 2894 (2014)] in connection with claimed observations of neutron emission in electrolytic cells is discussed. Real-time measurements of x-ray and neutron pulses by Agafonov *et al.* are commented on using the thorough study of the x-ray emissions by discharges under similar conditions [Kochkin *et al.*, J. Phys. D: Appl. Phys. **45**, 425202 (2012)].

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I. INTRODUCTION

Acceleration of electrons to high energies in dense layers of the atmosphere in electric fields of thunderclouds (electron runaway) predicted by Wilson [1] and for the first time trustworthily observed and initially studied in laboratory experiments at the end of 1960 through the first part of 1970 [2–8] now is considered a rather common process inherent for some laboratory and natural discharges (cf. [9–27] and citations therein). Wilson also predicted nuclear reactions in thundercloud fields [1]. The claimed observations of neutron flux enhancements in the thunderstorm atmosphere [28–36] could be a manifestation of the validity of this hypothesis; however concerns are expressed whether these observations are trustworthy [37–40]. Statistically significant detection of neutrons in laboratory discharges would be a serious argument in favor of the claimed observations of thunderstorm-correlated increases in neutron flux in the atmosphere; therefore, a communication on the first observations of "...the emission of neutron bursts in the process of high-voltage discharge..." in the atmosphere at standard temperature and pressure conditions [41] is of great interest for atmospheric electricity. In Ref. [41] rather common voltage pulses were applied at a gas-discharge gap with a spacing d up to 1 m [the amplitude was $U = 1$ MV, a rise time of 200 ns, and a total duration of 500 ns (Fig. 1)]. Current pulses were produced with the amplitude of 10–15 kA and a total duration of 500 ns, which were preceded by a low prepulse with a duration of $\Delta t_{\mathrm{pre}} \approx 250$ ns (Fig. 1). The authors communicate that neutron pulses with the duration of $\Delta t_n \approx 25$ ns were generated in the range from thermal energies "...up to energies above 10 MeV with an average flux density of 10^6 cm^{-2} per shot inside the discharge zone" [41]. Neutrons were detected at the initial phase of the discharge at the voltage plateau inside the x-ray pulse with a duration at the base of $\Delta t_x \approx 80$ ns, which terminated at the end of the prepulse current immediately at the beginning of the voltage collapse (Fig. 1).

The observation of x rays in Ref. [41] is evidence of a local enhancement of the field at least up to a magnitude of 30 MV m^{-1} atm^{-1} required for low-energy electrons to run away in air [6,9–11,42–44]. But for the neutron production in a dense atmosphere much stronger fields are required than for the generation of high-energy runaway electrons accounting for the bremsstrahlung x rays as observed in laboratory discharges in dense gases [2–27]. The neutron generation by discharges in the open atmosphere is extremely intriguing because a rather long voltage rise time of hundreds of nanoseconds [41] does not allow achieving high overvoltages at the interelectrode gap as a whole.

A goal of this paper is to verify whether neutron generation is theoretically really possible under the conditions as in the paper [41]. In Secs. II–IV this problem is analyzed in the framework of the known fundamental interactions, namely, nuclear synthesis and reactions induced by high-energy electrons: photonuclear reactions (γ,n) due to high-energy bremsstrahlung direct electrodisintegration $^n_mA(e^-,n)\ ^{n-1}_{m}A$ and opposite to the β-decay weak reactions $e^-(p^+,n)\nu_e$ [39,40]. In Sec. V the reliability of neutron measurements in Ref. [41] is discussed.

II. NUCLEAR SYNTHESIS

Initially let us address the nuclear synthesis, which conventionally, but erroneously, is considered as the fundamental process capable of accounting for the neutron emissions in a thunderstorm atmosphere [28–30,45,46]. Three neutron producing reactions of this kind are possible in air: $^2H(^2H,n)\ ^3He$, $^2H(^{14}N,n)\ ^{15}O$, and $^2H(^{12}C,n)\ ^{13}N$. From their cross sections σ_{fus}, available, in particular, in Ref. [47] for $^2H(^2H,n)\ ^3He$, in Refs. [48–51] for $^2H(^{14}N,n)\ ^{15}O$, and in Refs. [52–54] for $^2H(^{12}C,n)\ ^{13}N$ (Fig. 2), it is seen

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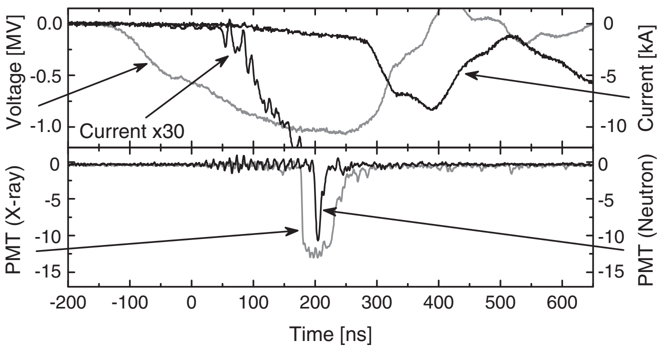

FIG. 1. Oscilloscope traces of current, voltage, x-ray, and neutron pulses measured with scintillation detectors coupled with PMTs [41]. X rays and neutrons are in relative units. (With permission of the authors of Ref. [41]).

that in the energy range of interest, i.e., below 1 MeV, the ^{2}H(^{2}H,n) ^{3}He reaction dominates. Nevertheless, in view of high nitrogen concentration in the atmosphere, on many orders of the magnitudes exceeding the deuterium concentration, it is reasonable to allow for the ^{2}H(^{14}N,n)^{15}O reaction. The reaction ^{2}H(^{12}C,n) ^{13}N can be discarded in view of the too low carbon concentration in air and too small cross section σ_{fus} in the energy range of interest.

On the grounds that kinetics of the deuterium ions in air with an imposed electric field is controlled by the charge transfer reaction $D^+ + N_2 \rightarrow D + N_2{}^+$, the neutron yield can be estimated as follows [55–58]:

$$N_n = N_n(\sigma_t = 0)\exp(-\varepsilon_{\text{fus}}/T), \quad (1)$$

where

$$N_n(\sigma_t = 0) \approx i n_D 2 N_L P\{[\text{H}_2\text{O}][\text{D}_2]\}\{[\text{N}_2]\} V\ \Delta t_n \langle v_{\text{ion}}\sigma_{\text{fus}}\rangle \quad (2)$$

is the neutron yield with ignored charge transfer, $T = eE/N_L P\langle\sigma_t\rangle$, E is the field strength, $\langle\sigma_t\rangle$ and $\langle v_{\text{ion}}\sigma_{\text{fus}}\rangle$, respectively, are the charge transfer cross section and the synthesis rate averaged over the deuteron distribution function, $N_L \approx 2.7 \times 10^{25}\text{m}^{-3}\ \text{atm}^{-1}$ is the number density of air molecules reduced to 1 atm (Loshmidt's number), P(atm) is the pressure, i is the ionization degree, $n_D = N_L P 2[\text{H}_2\text{O}][\text{D}]$ is the deuterium nuclei concentration, $[\text{H}_2\text{O}] \approx 1\%$ is the water percentage in air under laboratory conditions at 20 °C, $[\text{D}_2] = 0.015\%$ is the deuterium percentage in natural water, $[\text{N}_2] \approx 0.8\%$ is the nitrogen percentage in air, $v = S \times l$ is the volume of the channel with length l and cross section S where the synthesis occurs, $\Delta t_n \approx 25$ ns is the neutron pulse duration in Ref. [41], v_{ion} is the deuteron velocity, and ε_{fus} is some minimum energy of deuterons, below which the synthesis is inefficient. The magnitudes in brackets $\{[\text{H}_2\text{O}][\text{D}_2]\}$ or $\{[\text{N}_2]\}$, respectively, are to be used for the ^{2}H(^{2}H,n) ^{3}He or ^{2}H(^{14}N,n)^{15}O reactions.

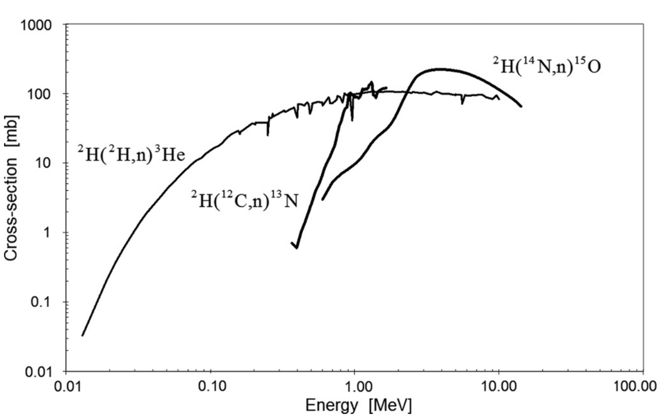

FIG. 2. Cross sections of reactions ^{2}H(^{2}H,n) ^{3}He [47], ^{2}H(^{14}N,n)^{15}O [48–51], and ^{2}H(^{12}C,n) ^{13}N [52–54].

S and l magnitudes required for calculating the volume v in (2) cannot be evaluated using dimensions of the channels bridging the interelectrode gap, available in the integral photograph in Ref. [27], because the neutrons were produced during the initial stage of the discharge with a rather slowly increasing prepulse current at the voltage plateau with $U_{\text{plat}} = 1$ MeV (cf. Fig. 1). Most likely, during this stage multiple separate electron avalanches and streamers were being developed such that the gap was not bridged up by a continuous channel; the bridging up occurred later during the observed sharp rise in the current up to the maximal value of 10 kA leading eventually to the voltage collapse. Hence, it is more or less reasonable to set the l magnitude be equal to the interelectrode spacing, i.e., of 1 m; however, it is not possible to set the S magnitude be equal to the area of the cross section of the channels bridging up the gap in Ref. [41]. Besides the ionization degree i also is undefined. Luckily, it is possible to eliminate both i and S using the relation $I(t) = en_e(t)v_d(t)S(t)$ for the current. Here $n_e(t) = i(t)N_L P$, $v_d(t) = \mu_e U(t)/l$, and $\mu_e \approx 0.09\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$ [59] are the electron concentration, drift velocity, and mobility in air, respectively. In the result formula (2) can be rewritten as follows:

$$N_n(\sigma_t = 0) = \frac{I\ \Delta t_n}{e\mu_e U} l^2 n_D 2P\{[\text{H}_2\text{O}][\text{D}_2]\}\{[\text{N}_2]\}\langle v_{\text{ion}}\sigma_{\text{fus}}\rangle. \quad (3)$$

With the use of this formula estimation from the above is possible for the neutron yield with the ignored charge transfer. According to the oscilloscope traces in Fig. 1 during the neutron generation the prepulse current I is of 400–500 A. Obviously the deuteron energy ε_{ion} could not exceed 1 MeV; therefore using $\langle v_{\text{ion}}\sigma_{\text{fus}}\rangle \approx v_{\text{ion}}\sigma_{\text{fus}}(\varepsilon_{\text{ion}})$ with absolutely unreal magnitude $\varepsilon_{\text{ion}} = 1$ MeV at which $v_{\text{ion}} \approx 10^7$ m/s and $\sigma_{\text{fus}} \approx 100$ and 10 mb (1 b $= 10^{-28}$ m^2), respectively, for the ^{2}H(^{2}H,n) ^{3}He and ^{2}H(^{14}N,n)^{15}O reactions (cf. Fig. 2), one can obtain $N_n(\sigma_t = 0) \approx 0.05$ for ^{2}H(^{2}H,n) ^{3}He and 2.5×10^4 for ^{2}H(^{14}N,n)^{15}O. Here it is taken into account that for acquiring the energy of 1 MeV an ion should cross the interelectrode gap such that by letting $\varepsilon_{\text{ion}} = 1$ MeV the generation domain length is limited to the magnitude no more than $0.1l \approx 0.1$ m or less near the cathode. Actually the deuteron energy is much less and, consequently, both v_{ion} and especially σ_{fus} are less. For instance, with $\varepsilon_{\text{ion}} = 0.1$ MeV and $l \approx 1$ m one can obtain $N_n(\sigma_t = 0) \approx 0.5$ for the ^{2}H(^{2}H,n) ^{3}He reaction. Using the extrapolation $\sigma_{\text{fus}}(\varepsilon) \approx$

$10.2\,\mathrm{mb} \times (\varepsilon/1\,\mathrm{MeV})^{2.67}$ for the $^{2}\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ cross section for low energies one can obtain $N_n(\sigma_t = 0) \approx 10^4$ neutrons for this reaction at $\varepsilon_{\mathrm{ion}} = 0.1\,\mathrm{MeV}$. Obviously all these evaluations of $N_n(\sigma_t = 0)$ are strongly overestimated.

To estimate the term $\exp(-\varepsilon_{\mathrm{fus}}/T)$ in (1), accounting for the charge transfer, E, σ_t, and $\varepsilon_{\mathrm{fus}}$ magnitudes are required. Above, on purpose, using the electric-field strength E was avoided, which, surely, is inhomogeneous, and local magnitudes of which are not known. Nevertheless, let us estimate $\exp(-\varepsilon_{\mathrm{fus}}/T)$ using the average strength $E = 1\,\mathrm{MV/m}$ and the energy $\varepsilon_{\mathrm{fus}} = 1.7\,\mathrm{keV}$ with which the $^{2}\mathrm{H}(^{2}\mathrm{H},n)\,^{3}\mathrm{He}$ cross section is negligibly small: $\sigma_{\mathrm{fus}} = 10^{-36}\,\mathrm{m}^2$ [60]. The $\mathrm{D}^+ + \mathrm{N}_2 \to \mathrm{D} + \mathrm{N}_2{}^+$ cross section is $\sigma_t \geqslant 4.25 \times 10^{-20}\mathrm{m}^2$ [61] in the energy range above $\varepsilon_{\mathrm{fus}} = 1.7\,\mathrm{keV}$. With this σ_t and $E = 1\,\mathrm{MV/m}$ one can obtain $T = eE/N_L P\langle\sigma_t\rangle \approx 0.87\mathrm{eV}$; hence $\exp(-\varepsilon_{\mathrm{fus}}/T)$ is almost zero. As noted above, the observation of x rays in Ref. [41] means that the strength E locally exceeded a magnitude of 30 MV/m, which is tenfold higher than the self-breakdown threshold in air at which the breakdown occurs leading to the voltage collapse. However, even such high strength does not allow overcoming the charge transfer. Consequently, the null neutron yield $N_n(\sigma_t = 0) \times \exp(-\varepsilon_{\mathrm{fus}}/T) = 0$ is expected. This is especially true in view of the other interactions of deuterium ions that are omitted, ionizing impacts, and elastic scattering, first of all.

III. UNCONVENTIONAL OPPORTUNITIES FOR THE NUCLEAR SYNTHESIS

Above, assuming linear acceleration of deuterons in an undisturbed electric field, nuclear synthesis was analyzed with a null result. Hence, either the events detected in Ref. [41] are not connected with nuclear synthesis, or the mechanism of the deuteron energizing is more complicated. Also there is a chance that the contemporary knowledge of the considered reactions is not complete. The following reasons are conceivable possibly allowing for the enhanced nuclear synthesis in the atmosphere:

(1) Collective acceleration of deuterons captured by electron flow as observed in beam plasmas [62–66]. Thus, for deuterons to acquire the energy of $\varepsilon_D = 0.1 - 1\,\mathrm{MeV}$, they are to be captured by a flux of electrons with the energy of the directed motion on the order of $\varepsilon_e \approx m_e\varepsilon_D/m_D \approx 27$–$270$ eV, which is not too high under the experimental conditions in Ref. [41]. Really, whereas with $U/Pd \approx 1\,\mathrm{MV}\,1\,\mathrm{atm}^{-1}\,1\,\mathrm{m}^{-1}$ the average energy of electrons in avalanches and streamers does not exceed a few eV [59], the energy of electrons in the electron avalanche and streamer fronts can be much higher owing to the local electric-field strengthening [6,9,10,59], which can be up to the magnitude of 30 MV/m permitting the electron runaway. However, the same difficulty remains due to the charge transfer in a dense atmosphere.

(2) Conventionally the synthesis of bare nuclei is considered. It is expected, however, that in the low-energy range the synthesis of nuclei shielded by electron shells may be more efficient because of the decreasing Coulomb barrier (cf., for instance, Refs. [60,67–73] and citations therein). The increase in the astrophysical factor $S(\varepsilon)$ is expected in the range of ultralow energies. This may be the case for fast deuterium atoms produced by the charge transfer $\mathrm{D}^+ + \mathrm{N}_2 \to \mathrm{D} + \mathrm{N}_2{}^+$ and deuterons participating in reactions $^{2}\mathrm{H}(^{2}\mathrm{H},n)\,^{3}\mathrm{He}$ and $^{2}\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ with $^{2}\mathrm{H}$ and $^{14}\mathrm{N}$ nuclei. But the expected deposition of the $S(\varepsilon)$ increase is rather obscure: It is necessary that the first multiplier in the cross section of nuclear synthesis $\sigma(\varepsilon) = \frac{S(\varepsilon)}{\varepsilon}\exp(-\mathrm{const}/\sqrt{\varepsilon})$ would overcome the exponential term; however, a sufficiently strong $S(\varepsilon)$ increase (on many orders of the magnitude) in the low-energy range is not observed by now.

(3) The $^{2}\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ and $^{2}\mathrm{H}(^{12}\mathrm{C},n)\,^{13}\mathrm{N}$ cross sections in the domain of low energies were assumed to decrease similarly to the $^{2}\mathrm{H}(^{2}\mathrm{H},n)\,^{3}\mathrm{He}$ cross section. However, this is not proved by direct measurements. Possibly, the $^{2}\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ and $^{2}\mathrm{H}(^{12}\mathrm{C},n)\,^{13}\mathrm{N}$ cross sections decrease to low energies not as fast as the extrapolation used above. Besides, because of the complicated structure of the $^{14}\mathrm{N}$ and $^{12}\mathrm{C}$ nucleons, resonances at low energies are conceivable with increased $^{2}\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ and $^{2}\mathrm{H}(^{12}\mathrm{C},n)\,^{13}\mathrm{N}$ cross sections. It is very unlikely, however, that the synthesis cross sections in the low-energy range increase on many orders of magnitude required for overcoming the charge transfer.

(4) The "cold synthesis" [74,75] is worth mentioning because it does not require high energies. However this effect, observed during prolonged saturation of metallic substrates with deuterium, is very unlikely under uncontrolled conditions in extremely short, of 100 ns, gas discharge as in Ref. [41].

(5) The $^{2}\mathrm{H}(^{12}\mathrm{C},n)\,^{13}\mathrm{N}$ reaction was ignored on the grounds of a too small carbon concentration in air, but it is necessary to keep in mind that electrodes of high-voltage sets, as a rule, are covered by oil films with high carbon concentration. However, a number of carbon nuclei in the films is too small in comparison with a number of nitrogen nuclei in the gas-discharge channel and, although the $^{2}\mathrm{H}(^{12}\mathrm{C},n)\,^{13}\mathrm{N}$ cross section is somewhat higher than that of $^{2}\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ (Fig. 2), the neutron yield remains null.

IV. NEUTRON REACTIONS INDUCED BY HIGH-ENERGY ELECTRONS

In the framework of the contemporary knowledge in Sec. II it was demonstrated that the nuclear synthesis is impossible in Ref. [41]. As the remaining three reactions, connected with high-energy electrons, are threshold ones, it is expedient to check if the applied voltage of 1 MV could allow for overcoming the thresholds.

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 correspondingly to $\varepsilon_{\mathrm{th,N}}(\gamma,1n) = 10.55\,\mathrm{MeV}$ and $\varepsilon_{\mathrm{th,O}}(\gamma,1n) = 15.7\,\mathrm{MeV}$ [39,40]. Electrons are required capable of producing bremsstrahlung with energies above 10.55 MeV that strongly exceeds 1 MeV.

Two electrodisintegration reactions by incident electrons with kinetic energy ε_e are relevant to the problem considered,

$$ {}^{14}_{7}\mathrm{N} + e^- + \varepsilon_e \to {}^{13}_{7}\mathrm{N} + n + e^-, \tag{4} $$

$$ {}^{16}_{8}\mathrm{O} + e^- + \varepsilon_e \to {}^{15}_{8}\mathrm{O} + n + e^-. \tag{5} $$

Their thresholds $\varepsilon_{\mathrm{th,N}}(e^-,n) = 10.55$ and $\varepsilon_{\mathrm{th,O}}(e^-,n) = 15.7$ MeV (the same as the photonuclear thresholds) also strongly exceed 1 MeV.

Opposite to the β decay are reactions with hydrogen nuclei of the water vapor,

$$ {}^{1}_{1}\mathrm{H} + e^- + \varepsilon_e \to n + \nu_e, \tag{6} $$

with threshold $\varepsilon_{\mathrm{th}}(e^-,n) = 0.783$ MeV [39,40] and reactions with the nuclei of the main constituents of the atmosphere,

$$ {}^{14}_{7}\mathrm{N} + e^- + \varepsilon_e \to {}^{13}_{6}\mathrm{C} + n + \nu_e, \tag{7} $$

$$ {}^{16}_{8}\mathrm{O} + e^- + \varepsilon_e \to {}^{15}_{7}\mathrm{N} + n + \nu_e, \tag{8} $$

with the same thresholds as reactions (4) and (5).

One can see that the thresholds of (γ,n) reactions, electrodisintegration reactions ${}^{n}_{m}A(e^-,n)\,{}^{n-1}_{m}A$ (4) and (5), and weak reactions (7) and (8) are too high for these reactions to be capable of accounting for the neutron production in air with the applied voltage of 1 MV. As the $e^-(p^+,n)\nu_e$ threshold $\varepsilon_{\mathrm{th}}(e^-,n) = 0.783$ MeV is lower than 1 MeV, one must address this reaction more attentively. Let us estimate a concentration n_e of high-energy electrons (in the analyzed case $\varepsilon_e \approx 1$ MeV) required for producing at least one neutron due to the $e^-(p^+,n)\nu_e$ reaction during the neutron generation time of $\Delta t_n \approx 25$ ns in Ref. [41]. Usage of the following formula for a number of neutrons is expedient,

$$ N_n \approx n_e \nu_{e^-,n} \Delta t_n = 1, \tag{9} $$

where for the rate $\nu_{e^-,n}$ of the $e^-(p^+,n)\nu_e$ reaction, a rate can be used for the "heavy" electron-proton interaction derived by Srivastava *et al.*, which in $\hbar = c = 1$ units reads as follows [76]:

$$ v_e \sigma_{e^-,n} \approx \frac{2G_F^2}{\pi}(\tilde{m}_e - \Delta)^2. \tag{10} $$

Here v_e is the electron velocity, $\sigma_{e^-,n}$ is the $e^-(p^+,n)\nu_e$ cross section; $G_F \approx 0.875 \times 10^{-37}$ eV cm^3 is the weak interaction constant (Fermi's constant); $\Delta = m_n - m_{p+}$ is the difference between neutron and proton masses in energy units; $\tilde{m}_e$ is a mass of the heavy electron, which in the framework of the problem considered is $\tilde{m}_e = m_e + \varepsilon_e$ [39,40]. Converting (10) to the international units, one obtains from (9) an unreal concentration of $n_e \approx 10^{48}$ m^{-3} of electrons with an energy of $\varepsilon_e \approx 1$ MeV, required for producing one neutron.

The electron energy, required for producing neutrons by electron-induced reactions, is too high for the experimental conditions in Ref. [41], unless the collective process of polarization self-acceleration occurs in front of avalanches and streamers [77] at the stage of the prepulse current in Ref. [41]. The self-acceleration allows energizing a small portion of electrons up to the energies exceeding the applied voltage as was observed in experiments with discharges at multiple overvoltages relative to the static self-breakdown voltage achieved using high-voltage pulses with subnanosecond fronts [9–11,78]. However, it seems absolutely impossible that electrons in sufficiently large numbers are capable of accelerating in a dense atmosphere even up to the energy of eU corresponding to the applied voltage of 1 MV, to say nothing of overcoming the ${}^{n}_{m}A(e^-,n)\,{}^{n-1}_{m}A$ thresholds.

V. DISCUSSION OF THE NEUTRON MEASUREMENT RELIABILITY

So, there is a dilemma: Either events observed in Ref. [41] are not connected with gas-discharge neutrons, or the neutrons' origin is more complicated than the considered above mechanisms, both acknowledged and hypothetical. *The author believes that signals in Ref. [41] were not due to gas-discharge neutrons.* Neutron measuring is an extremely sophisticated task not only due to usual electromagnetic noises, but, mainly, due to *the interference of other penetrating emissions, both accompanying the neutron generation under study and environmental*. Overcoming this difficulty is not a simple task, especially while measuring small neutron fluxes.

A. Track measurements. Neutron emissions in electrolytic cells

It would be expedient to ask the question if the track measurements in Ref. [41] were sufficiently accurate. C-39 track detectors used in Ref. [41] primarily are sensitive to fast neutrons, which were being registered in Ref. [41] with the efficiency of $\eta = 6 \times 10^{-5}$. For detecting thermal neutrons the CR-39 tracers were coupled with boron such that α particles $[{}^{10}\mathrm{B}(n,\alpha)\,{}^{7}\mathrm{Li}]$ create tracks with $\eta = 1.4 \times 10^{-6}$ [41]. Neutrons with energies above 10 MeV were detected using the carbon nuclei disintegration onto three α particles $n({}^{12}\mathrm{C}\,,n')3\alpha$ with $\eta = 1.2 \times 10^{-6}$ [41].

In context with neutron observations under unusual conditions the experiments on neutron emission by discharges in electrolytic cells [79–82] are worth mentioning, among which, in the author's opinion, the most accurate are those by Faccini *et al.* [82], who, although they write that they followed "...the observation of neutron production in high-voltage discharges..." in the atmosphere [41], actually checked the results by Cirillo *et al.* [81] who claimed a rather high (for electrolytic cells) neutron flux of 72000 n cm^{-2} s^{-1} measured with CR-39 tracers.

The dc feeding of the electrolytic cells is strongly different from the extremely short feeding in Ref. [41]; in particular in the experiments by Faccini *et al.* the feeding dc voltage and current were 150–300 V and 1.5–3.0 A, respectively, i.e., on the orders of the magnitude lower than in Ref. [41]. Nevertheless, for my goal these experiments are of great interest because Faccini *et al.* "have optimized and studied in detail ... CR-39 tracers ... and properly have taken into account the ambient background and its fluctuations," which allow "... evidencing features that would have not been observed otherwise ..." in such subtle measurements.

In Ref. [41] some CR-39 tracers were placed inside electrodes. In the experiments by Faccini *et al.* the detectors were located close to the cathode, namely, 5 cm when placed outside the cell and 2 cm when inside. For detecting thermal neutrons the tracers were wrapped with a 50-μm-thick layer of pure ^{10}B. Besides, in order to fit the experiment by Cirillo *et al.* [81], some tracers were additionally covered with a 1-cm-thick layer of boric acid. All conceivable systematic error contributions were taken into account, and a novel rigorous numerical approach was developed to allow for compatibility of the irradiated and background detector readings. In the first experimental campaign the CR-39 calibration constant $c = (6.9 \pm 0.3) \times 10^{-3}$ tracks/neutron was 70 times bigger than in Ref. [81], "... thus confirming the scarce sensitivity..." in Ref. [81]. Additionally for CR-39 tracers Faccini *et al.* used indium indicators (reaction ^{115}In(n,γ) ^{116}In, half-life of 54 min, and cross section from 1.5 b for partially moderated fast neutrons to 60 b for the thermal), which are the most sensitive neutron detectors. All detectors were being exposed to the cell emissions *several weeks after the calibration procedure* [82]. The obvious shortcoming is that the CR-39 tracers accumulated tracks due to environmental radiation. In these runs the CR-39 tracers presented (110–280)-n cm^{-2} s^{-1} deviation from the background, which is incompatible with the flux of 72 000 n cm^{-2} s^{-1} reported in Ref. [81]. Neither indium indicators nor the tracers with the thick boron coating (as in Ref. [81]) did expose statistically significant signals.

Furthermore, from 2-month background measurements Faccini *et al.* estimated that CR-39 tracers integrate $dD/dt =$ 3.8 tracks cm^{-2} day^{-1}, regardless of the boron presence, likely, due to cosmic radiation and radon contamination [82]. They noted that in the city of Naples where the experiment [81] was performed, *the track accumulation rate due to the environmental emissions was more than threefold higher*. Therefore, in the following campaigns by Faccini *et al.* the background detectors also were covered with the thin boron film and, *to avoid the track accumulation, were analyzed simultaneously with the detectors exposed to the emissions from the cell*. In these campaigns with $c = (8.3 \pm 0.8)\,10^{-3}$ tracks/neutron three detectors were wrapped in aluminum and three in cadmium in order to screen electromagnetic radiation and thermal neutrons, respectively. Both CR-39 and indium detectors yield signals consistent with the background with the exception of two Al-wrapped CR-39 tracers "... as though the wrapping could cause some spurious tracks" [82]. Faccini *et al.* concluded "... from the absence of signals in the indium disks, ... that the produced neutron flux is smaller than 1.5 or 64 n/cm^2/s...," respectively, for thermal or partially moderated neutrons according to the ^{115}In(n,γ) ^{116}In cross section.

Thus, in connection with the analysis of CR-39 tracers by Faccini *et al.* my concluding questions with respect to the high-voltage experiment in Ref. [41] are as follows.

(1) The CR-39 calibration constant $(8.3 \pm 0.8) \times 10^{-3}$ tracks/neutron in Ref. [82] is more than two orders of the magnitude higher than $1.4 \times 10^{-6} - 6 \times 10^{-5}$ in Ref. [41]. This means the scarce sensitivity in Ref. [41]; hence, the first question is as follows: "Were the background measurements and numerical procedure in Ref. [41] as rigorous as in the experiments by Faccini *et al.*?"

(2) To avoid the track accumulation due to the environmental radiation, Faccini *et al.* in their final campaigns analyzed the background CR-39 detectors simultaneously with the detectors exposed to the cell emissions. It seems that this was the case in Ref. [41] because according to the caption for Fig. 1 [41] "... background detectors were placed 10 m from the discharge." But Faccini *et al.* preliminarily have measured integrated track rates due to the environmental emissions. Hence, the second question is as follows: "Was a time lag between the exposures to the discharge emissions and counting of the tracks in Ref. [41] sufficiently short to avoid spurious signal accumulations both in the background detectors and in the detectors irradiated by the discharge?" These questions relate to the carbon disintegration reaction (sensitivity 1.2×10^{-6} [41]) as well.

(3) And eventually, why not use the neutron indicators, which are the most sensitive devices?

B. Real-time neutron and bremsstrahlung x-ray measurements

In addition to the C-39 tracers, scintillation detectors coupled with photomultiplier tubes (PMTs) were used in Ref. [41] for real-time measurements. Almost half of the discharges in Ref. [41] were observed to produce x-ray pulses, of which a portion of 25%–30% was combined with the neutron emissions (Fig. 1). All events of amplitude exceeding the background by 10% were considered as trustworthy, which in such a subtle experiment is insufficient.

As noted in the Introduction, the electron runaway accompanied by bremsstrahlung x rays is a rather common gas-discharge process. For my purpose the observations of x rays in very long discharges [22–27] is especially meaningful, among which one of the most illuminative is the experiment by Kochkin *et al.* [27], who "... measured the voltage and the current..., synchronized with nanosecond fast photography and x-ray detection..." with the "... aim... to find where and when the x rays are generated." The experiment by Kochkin *et al.* was carried out using a discharge configuration and feeding voltage very similar to those in Ref. [41]: open atmosphere, cone-shaped electrodes, 1-m interelectrode spacing, voltage pulses with amplitudes of 1 MV, rise times of 1 μs, and flat tops. During voltage rise a large and dense corona of positive streamers, emerging from the anode, was observed. Near the cathode the positive corona was being connected with the relatively weak corona of the negative counterstreamers emerging from the cathode.

The x rays were recorded by LaBr3(Ce+) scintillation detectors coupled with PMTs (1-ns time resolution) located in electromagnetic compatibility cabinets. The discharges produced up to three x-ray peaks with half-width durations of 50 ns during a time span of 0.8 μs until the beginning of the voltage collapse. The first peak was generated during the slow cathode current rise (as in Ref. [41]) at the voltage front, unlike in Ref. [41] where the x rays and neutrons appeared at the voltage plateau. The first peak maximum was at the voltage of 0.8 MV when the cathode current was 100 A. The energy of the second peak was comparable to or larger than the first. The predominant photon energy ε_γ was somewhat above 200 keV with the spectrum extended up to $\varepsilon_\gamma = 1$ MeV. A single event with ε_γ up to 3.4 MeV was observed. Most likely, the high-energy events are caused by fast bursts of lower-energy photons [22]. The x-ray signals were observed to correlate in time with cathode current oscillations and the connection of positive and negative coronas. From this Kochkin *et al.* assumed that exactly positive and negative "... streamer encounters generate ns-fast x-ray bursts" [27].

Whatever may be the underlying mechanism, the x-ray production itself means that during streamer encounters locally nanosecond or even shorter jumps of electric-field strength occurred at least up to the runaway threshold of 30 MV/m. All streamer encounters were accompanied by high-frequency current oscillations, possibly, evidencing such jumps. Significantly, that onset of the first x-ray peak coincides with the especially strong oscillations of 100 A. This is true for the first and second peaks and on a much less degree for the third.

Thus, in connection with the high-voltage x-ray experiment [27] carried out under the same conditions as the neutron experiment [41] my comments are as follows:

(1) The duration at the base of each x-ray peak in Ref. [27] is almost the same as in Ref. [41]: $\Delta t_x \approx 80$ ns. But in Ref. [27] each x-ray signal was of triangular form whereas in Ref. [41] a trapeziumlike (almost rectangular) signal with a weakly oscillatory top was recorded as if consisting of a superposition of a series of consecutive triangular pulses with equal heights, which is very unlikely.

(2) In Ref. [27] electrons acquired high energies near the cathode in the domains with an enhanced field where positive streamer corona met negative counterstreamers from where they run away and produce x rays throughout the ambient matter; hence one can expect that in Ref. [41] the neutron source also was near the cathode. However, the neutron fluence per shot measured by C-39 tracers located in the cathode and anode was almost the same: $2 \times 10^5\, n/\mathrm{cm}^2$ vs $3 \times 10^5\, n/\mathrm{cm}^2$ [41].

(3) The real-time measured neutron pulse is inside the x-ray pulse in Ref. [41]. The neutron energy of 15-7 MeV evaluated using the time shift of the pulses offsets cannot be prescribed to any known fundamental interaction. Because "no neutron pulses were observed out of the x-ray pulse" [41] and one needs to be confident that the neutron pulse is not due to some kind of electromagnetic radiation, including penetrating emissions, for instance, the high-energy bremsstrahlung photons from the discharge, it is necessary to check if the neutron pulse offset relative to the x-ray offset displaces along with the detector displacement.

VI. CONCLUSIONS

The observations of the neutron generation by laboratory discharges in the open atmosphere reported in Ref. [41] were analyzed; it was demonstrated that known fundamental interactions cannot allow prescribing the observed events to neutrons. Nuclear synthesis, $^2\mathrm{H}(^2\mathrm{H},n)\,^3\mathrm{He}$ and $^2\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$, with the participation of atmospheric deuterons is not capable of the neutron production under the conditions in Ref. [41]. Even with the deuteron energy of 1 MeV, corresponding to the applied voltage [41], an undetectable neutron yield was computed under the conditions in Ref. [41]. Allowing for the charge transfer reactions gives a null neutron yield.

Unconventional opportunities for the nuclear synthesis to occur in an electric field in the atmosphere were discussed; some of them (collective acceleration and cold synthesis) were really observed elsewhere but under conditions strongly different from those in Ref. [41], and the others are too hypothetical and require special theoretical consideration and experimental research [increased cross sections of $^2\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ and $^2\mathrm{H}(^{12}\mathrm{C},n)\,^{13}\mathrm{N}$ reactions in the low-energy range and increased cross sections of synthesis of nuclei shielded by electron shells].

A possibility of neutron generation by photonuclear and electrodisintegration reactions was discarded on the grounds of too high thresholds in comparison with the applied voltage in Ref. [41]. Unreal concentration of free electrons in a gas-discharge plasma is required in order to prescribe the neutron production to the opposite of the β-decay reaction, which is discussed in connection with the so-called low-energy nuclear reactions and, in particular, with the neutron generation in a thunderstorm atmosphere [39,40,76].

In connection with the nuclear synthesis in general especially intriguing is the reported detection of neutrons with energies above 10 MeV [41] because total energy yields of all products of reactions $^2\mathrm{H}(^2\mathrm{H},n)\,^3\mathrm{He}$ (3.270 MeV [64]) and $^2\mathrm{H}(^{14}\mathrm{N},n)\,^{15}\mathrm{O}$ (5.068 MeV [83]) are less than 10 MeV. Neither conventional nor unconventional processes are capable of accounting for such high energy, which, most likely, indirectly testifies to some shortcomings in the experiment, most likely, in the calibration or data processing. Comparing the CR-39 tracer sensitivity in Ref. [41] with that in the paper by Faccini *et al.* [82], the scarcity of sensitivity in Ref. [41] was found. It is not clear if the delay in the data processing was sufficiently short to avoid spurious track accumulation both in the irradiated and in the background detectors in Ref. [41].

In Ref. [41] "an average flux density of $10^6\, n/\mathrm{cm}^2$ per shot was detected inside the discharge zone," but the discharge channel (the discharge zone) length is too large for this statement to be informative, especially for the detectors located in the electrodes. It is unclear by what area the magnitude of $10^6\, n/\mathrm{cm}^2$ is to be multiplied to receive the absolute neutron yield. In the view of Ref. [27] under the same conditions the x-ray emission was coincident with encounters of positive and negative streamers in the near-cathode domain, during which the high-energy processes occurred, and one can expect that in Ref. [41] the neutron source also was closer to the cathode and, therefore, readings of the tracers located in the cathode significantly exceed those of the anode tracers, but this is not the case. To understand the origin of the penetrating emissions from discharges in such a dense medium as the lower atmosphere, it is very important to localize a domain of neutron generation or, at least, a source of the accompanying x rays as has been performed in experiments with laboratory discharges in the atmosphere [13–17] with the use of voltage pulses with rise times of 10 ns allowing for electric fields with much higher average strength *U/d* than in Ref. [41] or under conditions similar to those in Ref. [41] as in the experiment by Kochkin *et al.* [27].

Using gas-discharge helium detectors, planned by the authors of Ref. [41], will not allow avoiding the difficulty of interference of the ambient radiation because these detectors are sensitive to any ionizing radiation, not only to neutrons [37–40]. The neutron indicators and time-of-flight technique are the most adequate for neutron measurements.

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