# Possible detection of high-energy photons from ball lightning

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It is shown that photons of the prolonged emission recorded by the Gamma-Ray Observation of Winter Thunderclouds (GROWTH) experiment on January 13, 2012 [D. Umemoto *et al.*, Phys. Rev E **93**, 021201(R) (2016)] could be emitted by ball lightning and generated by annihilation of positrons which arose mainly due to production of the $\beta^+$-active isotopes by the sharp $\gamma$-ray flash, accompanying the formation of ball lightning, and production of electron-positron pairs by photons from ball lightning. The model of ball lightning is based on the assumption that ball lightning has a core consisting of clouds of electrons and almost totally ionized ions which oscillate with respect to each other.

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## I. INTRODUCTION

The assumption that ball lightning emits ionizing radiation, in particular high-energy photons, has been discussed for many years and is in agreement with a number of reports about physical and biological effects caused by ball lightning [1–10], for example, the recent report about glass window fluorescence that could be caused only by UV or harder radiation [10], but the reliable detection of such radiation has not been performed. It is possible that Dmitriev detected $\gamma$ rays in the vicinity of ball lightning with a scintillation $\gamma$ radiometer, but the indication of his radiometer might also be induced in the photomultiplier by radio waves from ball lightning [2,4]. Ashby and Whitehead undertook a search for high-energy photons from ball lightning, assuming that ball lightning was the manifestation of an antimatter meteorite [3,7]. Four $\gamma$-ray fluxes lasting a few seconds were detected, but their association with ball lightning and even with thunderstorms was not clearly established, although one of them did occur during a local thunderstorm in the situation that was favorable, according to other observational data [8], for the formation of ball lightning, namely, "in rough coincidence with a lightning bolt striking a flagpole about 100 yards from the gamma ray detection crystals" [7]. The fact that both durations of many fluxes of high-energy photons detected during thunderstorms and ball lightning lifetime $\tau_{\rm bl}$ are in the range from about one to a few hundred s [1,2,4,11–17] allows us to assume that some of these fluxes were completely [9] or partly generated by ball lightning. This assumption and the ball lightning model proposed in Ref. [8] are in agreement with some of the parameters of high-energy photon flux detected by the Gamma-Ray Observation of Winter Thunderclouds (GROWTH) experiment of January 13, 2012 [15].

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## II. SOME OBSERVATIONAL DATA FROM THE GROWTH EXPERIMENT

On January 13, 2012, the NaI detector of the GROWTH experiment, located in the Kashiwazaki-Kariwa nuclear power plant in Niigata prefecture, Japan, recorded a sharp $\gamma$-ray flash with a duration less than 300 ms, followed by a prolonged $\gamma$-ray emission lasting for about 60 s [15]. The sharp flash was recorded in coincidence (within 300 ms) with an intracloud discharge which occurred at the horizontal distance $l_d \approx 300 \pm 150$ m from the detector [15]. The spectrum of the prolonged emission had the upper boundary $\varepsilon_{\max} \approx 6.5-10$ MeV and was a superposition of the continuum and a line with the center at about $503 \pm 3$ (statistical)$\pm 5$ (systematic) keV (the systematic error refers to the calibration uncertainty) [15]. This line was identified with an electron-positron annihilation line [15]. For the prolonged emission, the numbers $N$, $N'$, and $N_l$ of photon counts corresponding to the 0.12–10 MeV and 0.45–0.56 MeV energy ranges and the annihilation line were $5340 \pm 190$, $780 \pm 50$, and $520 \pm 50$, respectively [15]. Thus, the contribution $N_c{}' = N' - N_l$ of the continuum into $N'$ equaled $260 \pm 70$. For the annihilation line, the effective area $S_l^{\rm eff}$ of the detector was $19 \pm 3$ (statistical) $\pm 2$(systematic) cm$^2$ [15]. Figures 1(c) and 1(d) of Ref. [15] yield that the duration $t_c{}'$ of the continuum in the 0.45–0.56 MeV energy range was about 45–60 s.

Let us compare the aforementioned data from the GROWTH experiment with those obtained on February 6, 2017 when two lightning discharges occurred in the vicinity of the same power plant and four detectors of this experiment simultaneously recorded an intense $\gamma$-ray flash lasting for about 200 ms [17]. The horizontal distances between the discharges and the detectors were about 0.5–1.7 km [17]. These distances are comparable with $l_d$. The flash consisted of a strong flash with a duration of less than 1 ms and afterglow with an exponential decay constant of 40–60 ms and the upper boundary of the spectrum of 7–10 MeV [17]. After the afterglow, two detectors, labeled A and D in Ref. [17], recorded in the 0.35–0.6 MeV energy range a photon flux lasting for about one minute. The prolonged emission and the

 

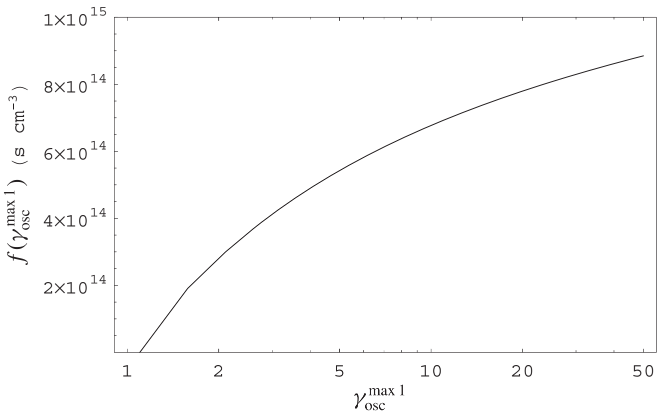


FIG. 1. The function $f(\gamma_{\rm osc}^{\rm max\,1})$ at $1.1 \leqslant \gamma_{\rm osc}^{\rm max\,1} \leqslant 50$.

afterglow were explained as the results of several photonuclear reactions, in particular, $^{14}{\rm N} + \gamma \rightarrow {}^{13}{\rm N} + n$, initiated by the initial strong $\gamma$-ray flash and generating fast neutrons and $\beta^+$-active isotopes $^{13}$N, $^{15}$O, $^{27}$Si, and $^{26{\rm m}}$Al with half lives of 598, 122, 4.15, and 6.35 s, respectively [17]. The afterglow arose due to emission of deexcitation $\gamma$ rays from nuclei capturing the neutrons [17]. The prolonged emission arose due to annihilation of positrons emitted by the $\beta^+$-active isotopes [17]. The apparent upper boundary of its spectrum was determined by the photon energy of about 0.511 MeV and the energy resolution of the instruments [17]. The absence of photon counts in the energy range above 0.6 MeV is the important difference of the prolonged emission recorded on February 6, 2017 from that recorded on January 13, 2012. The photon count rate $R_{\rm pr}^{\rm count}$ of the prolonged emission recorded by detector D was described as an exponentially decaying component resulting from production of the $^{27}$Si and $^{26{\rm m}}$Al isotopes in the detectors and materials around them [17]. For detector A, $R_{\rm pr}^{\rm count}$ was described as a sum of a similar decaying component and a subsequent delayed component resulting from production of the $^{13}$N and $^{15}$O isotopes in air and their motion with wind [17]. The numbers of counts of photons of the decaying components by detectors A and D were about 470 and 370, respectively [17]. These values and their ratios to the effective detector areas at 0.511 MeV (142.2 cm$^2$ for detector A and 28.3 cm$^2$ for detector D) are comparable with $N_l$ and $N_l/S_l^{\rm eff}$, respectively.

## III. THE MAIN MODEL ASSUMPTIONS, BALL LIGHTNING LIFETIME, AND SPECTRUM OF HIGH-ENERGY PHOTONS FROM BALL LIGHTNING

The ball lightning model proposed in Ref. [8] and the data from Refs. [15] and [17] yield that photons of the prolonged emission recorded on January 13, 2012 could be emitted by ball lightning and generated by annihilation of positrons which arose mainly due to production of the $\beta^+$-active isotopes by the sharp $\gamma$-ray flash, accompanying the formation of ball lightning, and production of electron-positron pairs by photons from ball lightning. The model is based on the assumption that ball lightning has a core consisting of clouds of electrons and almost totally ionized ions which oscillate with respect to each other [8]. The core is surrounded by the depleted layer which isolates it from the atmosphere [8,18]. The stability of the core is provided by the oscillation of its particles and the atmospheric pressure transferred through the depleted layer [8,18].

The initial acceleration of electrons of the core results from their attraction to the positive charge injected into the atmosphere and the effect usually called "cold runaway" or "thermal runaway" [8,9,13,19–23]. In the situations corresponding to the GROWTH experiment, such injection probably occurs at the stage of the return stroke in the region of propagation of negative or positive leader of ordinary lightning [19]. Other scenarios for the injection are also possible [8,19]. The terms cold runaway and thermal runaway describe the situation when the strength of the electric field in gas or plasma is so high that the electron, influenced by this field, acquires high kinetic energy or, in other words, becomes runaway, at any initial kinetic energy [13,20–23]. Many modes of oscillation of electron are excited initially, but the losses of energy due to the emission of radio waves quickly attenuate almost all of them except for a spherically symmetrical one and, in some situations, a few others [19]. Below, for the sake of simplicity, only a spherically symmetrical ball lightning core will be considered. Its electrons and ions oscillate in radial directions. In especially interesting and important situations corresponding to relatively high volume densities of ball lightning energy and long $\tau_{\rm bl}$, such core generates photons and loses energy mainly due to bremsstrahlung and the amplitude $A_e$ of oscillation of the electrons is much less than its radius $R_c$ [8,18]. The latter enables us to describe the oscillation within the framework of a one-dimensional model (the amplitude of oscillation of the ions is much less than $A_e$) [8].

The ball lightning core has the positive electric charge arising due to the escape of some of the electrons from it [8]. This charge is much less than the absolute value of the charge of all of the electrons of the core. Therefore, inside the core, the electron density $n_e$ is about $\langle Z\rangle n_i$, where $\langle Z\rangle \approx 7.262$ is the average value of atomic number $Z$ of the components of the air and $n_i$ is the density of the ions [8]. The maximum energy of the photon emitted during some period of oscillation is about the maximum value $\varepsilon_{\rm osc}^{\rm max}$ of the electron kinetic energy corresponding to its oscillatory motion [8,18]. The typical initial values $\varepsilon_{\rm osc}^{\rm max\,1}$ of $\varepsilon_{\rm osc}^{\rm max}$ are of the order of 0.1–10 MeV [8]. At $\gamma_{\rm osc}^{\rm max\,1} = \varepsilon_{\rm osc}^{\rm max\,1}/(mc^2) + 1 \geqslant 1.1$, where $m$ is the rest mass of the electron and $c$ is the velocity of light, $\tau_{\rm bl}$ is about the time of a decrease in $\varepsilon_{\rm osc}^{\rm max}$ down to 10 keV and can be described as

$$\tau_{\rm bl} \approx f\big(\gamma_{\rm osc}^{\rm max\,1}\big)/n_i + \tau_{\rm bl}\big(\gamma_{\rm osc}^{\rm max\,1} = 1.1\big), \tag{1}$$

where $f(\gamma_{\rm osc}^{\rm max\,1})$ is a function that depends only on $\gamma_{\rm osc}^{\rm max\,1}$ and $\tau_{\rm bl}(\gamma_{\rm osc}^{\rm max\,1} = 1.1)$ is the time of a decrease in $\varepsilon_{\rm osc}^{\rm max}$ from $0.1mc^2 \approx 51.1$ keV to 10 keV [9,18]. At standard conditions, $\tau_{\rm bl}(\gamma_{\rm osc}^{\rm max\,1} = 1.1) \approx 0.8$–$2$ s [18]. For $1.1 \leqslant \gamma_{\rm osc}^{\rm max\,1} \leqslant 50$, $f(\gamma_{\rm osc}^{\rm max\,1})$ is plotted in Fig. 1. Equation (1) was derived assuming, in particular, that $n_i$ does not depend on time and the core is almost uniform or consists of a more or less uniform region with $n_i \neq 0$ and the region around ball lightning center which can be considered empty [9]. The former assumption is based on the reports about ball lightning with constant or

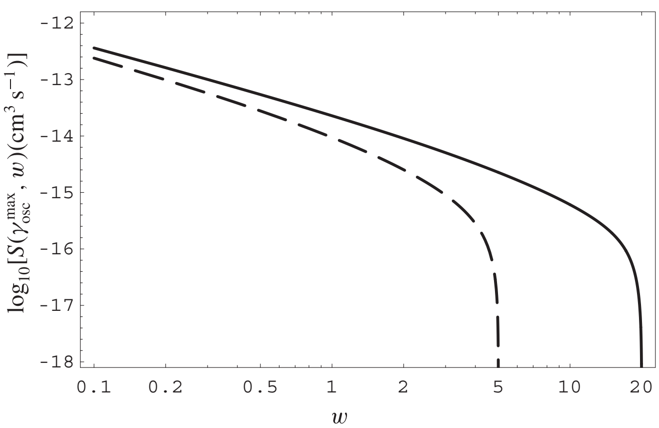


FIG. 2. The functions $\log_{10}[S(\gamma_{osc}^{max}, w)(cm^3\,s^{-1})]$ at $\gamma_{osc}^{max} = 6$ (dashed line) and 21 (solid line).

approximately constant sizes [4]. Other details are presented in Refs. [8,9,18].

The average rate $d\overline{R}$ of emission of photons with energies from $mc^2 w$ to $mc^2(w + dw)$ is given by

$$d\overline{R} \approx n_i n_e S\big(\gamma_{osc}^{max}, w\big)dw, \tag{2}$$

where $S(\gamma_{osc}^{max}, w)$ is a function that depends only on $\gamma_{osc}^{max}$ and $w$ [8,9]. The examples of $\log_{10}[S(\gamma_{osc}^{max}, w)(cm^3\,s^{-1})]$ for $\gamma_{osc}^{max} = 6$ and 21 (the situations with such $\gamma_{osc}^{max}$ are discussed below) and $0.1 \leqslant w \leqslant \gamma_{osc}^{max} - 1$ are plotted in Fig. 2.

## IV. PROPAGATION OF PHOTONS FROM BALL LIGHTNING TO THE DETECTOR AND ILLUSTRATIVE EXAMPLES

Let us consider initially the situation when photons from ball lightning interact only with air and the detector, the effective area $S^{eff}$ of the detector is independent of the direction of propagation of the photon, and, at least in the 0.45–0.56 MeV energy range, on photon energy, and the distance $d$ between ball lightning and the detector and the air density $\rho_{air}$ in the physically important region of propagation of high-energy photons from ball lightning to the detector are constant or almost constant. In such situation, a photon with energy $\varepsilon_{phot} = 0.45-0.56\,\text{MeV}$, emitted by the ball lightning in an arbitrary direction, will be detected in the 0.45–0.56 MeV energy range with the probability $p_d$, which can be calculated as

$$p_d \approx \frac{S^{eff}}{4\pi d^2} k_b[\varepsilon_{phot}, d/l_c(\varepsilon_{phot})] \exp[-d/l_c(\varepsilon_{phot})], \tag{3}$$

where $k_b$ is the buildup factor, taking into account propagation of the photon without scattering and its scattering without a decrease in energy lower than 0.45 MeV, and $l_c$ is the typical length of Compton scattering in the air [24,25]. Emission of a photon with $\varepsilon_{phot} > 0.56$ MeV by the ball lightning can be accompanied by its scattering, providing a subsequent detection in the 0.45–0.56 MeV energy range. It is convenient to calculate the probability $p_d^s$ of such detection as

$$p_d^s \approx \frac{S^{eff}}{4\pi d^2} k_s(\varepsilon_{phot}, d) \exp[-d/l_i(\varepsilon_{phot})], \tag{4}$$

where $k_s$ is the factor describing the possibility of scattering mentioned above and $l_i$ is the typical length of interaction of photon with air. At 0.56 MeV $\leqslant \varepsilon_{phot} \leqslant 2mc^2 \approx 1.022$ MeV, $l_i = l_c$, while at $\varepsilon_{phot} > 2mc^2$, $l_i \approx (1/l_c + 1/l_p)^{-1}$, where $l_p$ is the typical photon path corresponding to production of an electron-positron pair; for $\varepsilon_{phot}$ and $d$ considered here, photoelectric absorption and that due to photonuclear reactions are negligible [24–28].

When calculating $k_b$, $k_s$ and the buildup factors mentioned below, the scattered radiation spectra tabulated by Goldstein and Wilkins [24] for scattering of photons from a point isotropic source in water were used. At the fixed $\varepsilon_{phot}$ and $d/l_c$ or $d/l_i$, buildup factors describing the scattering of photons in air and water approximately coincide [25], and it is possible to show that the situation with $k_s$ is the same. Since the data presented in Ref. [15] were obtained during a winter thunderstorm and the Kashiwazaki-Kariwa nuclear power plant is located at an altitude of about 30–40 m [12,17], the calculations were performed for standard conditions.

Let us assume that $\gamma_{osc}^{max\,1} \approx 21$ (this choice corresponds to $\varepsilon_{max}$ and the assumption that thunderstorm electric fields did not cause physically important runaway [13,29] of electrons and positrons accelerated or created by high-energy photons from ball lightning in air), in the 0.45–0.56 MeV energy range $S^{eff} \approx S_l^{eff} \approx 19\,\text{cm}^{-2}$, while

$$d = 2\,\text{km} \tag{5}$$

and the observable registration of the continuum in the 0.45–0.56 MeV energy range lasts for about 50 s (see the value of $t_c'$ presented above) and ends at $\gamma_{osc}^{max} = \gamma_{osc}^{max\,2} \approx 6$. The last assumption is based on the fact that at $\gamma_{osc}^{max\,1} \approx 21$ and $d = 2$ km, the number of photons of the continuum with energies under consideration, detected after a decrease in $\gamma_{osc}^{max}$ down to six, is only about 0.45% of that detected during the decrease and, therefore, can be considered negligible. Below, this relationship will be used to estimate $\gamma_{osc}^{max\,2}$ at other $d$. Equation (1) yields that the time $t_d(\gamma_{osc}^{max\,1}, \gamma_{osc}^{max\,2})$ of a decrease in $\gamma_{osc}^{max}$ from $\gamma_{osc}^{max\,1}$ to $\gamma_{osc}^{max\,2}$ is given by

$$t_d\big(\gamma_{osc}^{max\,1}, \gamma_{osc}^{max\,2}\big) \approx \big[f\big(\gamma_{osc}^{max\,1}\big) - f\big(\gamma_{osc}^{max\,1} = \gamma_{osc}^{max\,2}\big)\big]/n_i. \tag{6}$$

Using Eqs. (1) and (6) and assuming that $\tau_{bl}(\gamma_{osc}^{max\,1} = 1.1) \approx 1$ s, we obtain that $t_d(21, 6) \approx 50$ s corresponds to registration of scattered and nonscattered photons from ball lightning with $n_i \approx 4.08 \times 10^{12}\,\text{cm}^{-3}$, $n_e \approx 2.96 \times 10^{13}\,\text{cm}^{-3}$, and

$$\tau_{bl} \approx 194\,\text{s}, \tag{7}$$

while Eqs. (2)–(5) yield that during a decrease in $\gamma_{osc}^{max}$ from 21 to 6, one electron of the ball lightning core brings into $N_c'$ the contribution $N_{ce}'$ of about $4.9 \times 10^{-15}$. Using this value and $N_c'$ and $n_e$ mentioned above, we obtain that the ball lightning core volume $V_f$ filled with electrons and ions is about $1.8 \times 10^3\,\text{cm}^3$. According to a one-dimensional model, $A_e$ is about $\sqrt{\varepsilon_{osc}^{max}/(2\pi e^2 n_e)}$, where $e$ is the absolute value of the electron charge [8]. At $\gamma_{osc}^{max} = 21$ and $n_e \approx 2.96 \times 10^{13}\,\text{cm}^{-3}$, $A_e \approx 0.62$ cm. Assuming that the radius of the empty region around the ball lightning center is negligible, we obtain $R_c \approx [3V_f/(4\pi)]^{1/3} + 2A_e$ (the first addendum in the right-hand side of this formula is the radius of a ball with volume $V_f$, while the second one approximately describes an increase in $R_c$ due to the motion of inner and outer boundaries of the electron cloud). This estimate yields $R_c \approx 8.7$ cm and shows that the condition $A_e \ll R_c$ of applicability of a one-dimensional model is satisfied even just after the formation of ball lightning. A visible ball lightning radius $R_{\rm bl}$ is greater than $R_c$ because the ball lightning core is surrounded by the depleted layer and UV radiation from ball lightning causes luminescence of the air near it [2,8,18]. The observational data allow us to assume that at $R_c$ of several cm, the difference between $R_{\rm bl}$ and $R_c$ is in the range from several mm to about 2 cm [2,8]. Thus, $R_c \approx 8.7$ cm corresponds to $R_{\rm bl} \approx 9-11$ cm. Both the last value and Eq. (7) are in agreement with the observational data [2,4].

Let us consider the influence of a decrease in $\rho_{\rm air}$ with altitude and the real conditions of the GROWTH experiment on $N_{ce}'$.

If ball lightning arose near the head of one of the leaders of ordinary lightning [4,9,19], the initial value $l_{\rm bl1}$ of the horizontal distance $l_{\rm bl}$ between the ball lightning and the detector was in the range of the possible values of $l_d$. Equation (5) and $l_{\rm bl} \approx 150-450$ m correspond to the difference $\Delta h_{\rm bl}$ of the altitudes of ball lightning and detector of about 1950–1990 m, while an increase in altitude on about 2 km results in a relative decrease in $\rho_{\rm air}$ on about 18% [25]. The main part of $N_{ce}'$ is related to the emission of photons with relatively high energies. For example, $\varepsilon_{\rm phot} \geqslant 2$ MeV and $\varepsilon_{\rm phot} \geqslant 3$ MeV correspond to about 94 and 75% of $N_{ce}'$, respectively. The data from Ref. [24] yield that the dependence of $k_s$ on $d/l_i(\varepsilon_{\rm phot})$ is close to linear. At standard conditions, $l_i(\varepsilon_{\rm phot} = 10\,{\rm MeV}) \approx$ 380 m; a decrease in $\varepsilon_{\rm phot}$ results in a decrease in $l_i$ [24–28]. Thus, at standard conditions and $d$ of about 2 km, a decrease in $p_d^s$ with increasing $d$ is mainly determined by the factor $\exp[-d/l_i(\varepsilon_{\rm phot})]$, which is equal to the probability $p_{\rm ns}$ of propagation of the photon without interaction with molecules of the air [24,25]. Equations (3)–(5) yield that a 10% decrease in $\rho_{\rm air}$ from the value corresponding to the standard conditions results in an approximately twofold increase in $N_{ce}'$. A proper decrease in $R_{\rm bl}$, taking into account the change in $\gamma_{\rm osc}^{\max 2}$ (also see below), can compensate for this increase. However, for illustrative examples of $d$ and $R_{\rm bl}$, it is preferable to choose the value $d = 2.2$ km, providing the approximate equality of $p_{\rm ns}$ for the propagation of photons in real atmosphere with standard conditions at sea level to $p_{\rm ns}$ at $\rho_{\rm air} =$ const, standard conditions and $d = 2$ km, and $R_{\rm bl} \approx 10-12$ cm [the increase in $R_{\rm bl}$ compensates for a decrease in the factor $(1/d^2)$ in the right-hand side of Eq. (4) with increasing $d$ at the fixed product $\rho_{\rm air} d$]. This is related to the relatively weak influence of ball lightning motion with wind and the real geometry of the GROWTH experiments on $N_{ce}'$ at $\Delta h_{\rm bl} \gg l_{\rm bl1}$. If the initial value $d_1$ of $d$ equaled 2.2 km, the initial value $\Delta h_{\rm bl1}$ of $\Delta h_{\rm bl}$ was about 2150–2190 m, much greater than $l_{\rm bl1}$. At least at some directions of wind and its velocity up to about 10 m/s, the motion of ball lightning with wind could not cause an important change of $d$, while the relation

$$\Delta h_{\rm bl} \gg l_{\rm bl} \tag{8}$$

could remain valid for the whole time of recording of the continuum. The propagation of scattered high-energy photons from any source to the detectors of the GROWTH experiment is influenced by high-density materials of the buildings on the roofs of which the detectors are placed, ground, and sea water [12,15,17,24,25]. However, if the continuum recorded on January 13, 2012 was associated with ball lightning, the influence of buildings, etc. on its parameters could be weak. According to Eq. (8) and the computer simulation data from Ref. [25], at least about 80% of scattered photons from ball lightning hit the detector after scattering only in the air. Thus, the effect of the scattering of photons in the high-density materials on the accuracy of the calculation of $N_{ce}'$ is about that of indeterminacy of $S_l^{\rm eff}$ or less.

In the situations under consideration, the presence of water in the air decreases $l_i$ on about 1.4% or less [25] and can be considered negligible.

It is evident that $N'$ and $t_c'$ from Ref. [15] also correspond to other $d$, $\gamma_{\rm osc}^{\max 2}$, and $\gamma_{\rm osc}^{\max 1}$. However, for the illustrative example, the choice made above is close to the optimum. For example, using $d = 2.5$ km instead of Eq. (8) and $\gamma_{\rm osc}^{\max 1} = 21$, we obtain $N_{ce}' \approx 5.3 \times 10^{-16}$, $n_i \approx 3.46 \times 10^{12}\,{\rm cm}^{-3}$, $n_e \approx 2.51 \times 10^{13}\,{\rm cm}^{-3}$, $\gamma_{\rm osc}^{\max 2} \approx 7$, and $\tau_{\rm bl} \approx 228$ s. An increase in $R_{\rm bl}$ can compensate for the decreases in $N_{ce}'$ and $n_e$, while an increase in $d$ and, as a result, in $\Delta h_{\rm bl}$ is a factor suppressing, as mentioned earlier, the importance of motion of ball lightning with wind. However, the last value of $\tau_{\rm bl}$ seems to correspond to relatively rare observations of ball lightning [4]. In turn, using $d = 1.5$ km and $\gamma_{\rm osc}^{\max 1} = 21$, we obtain $N_{ce}' \approx 5.8 \times 10^{-14}$, $n_i \approx 5.05 \times 10^{12}\,{\rm cm}^{-3}$, $n_e \approx 3.67 \times 10^{13}\,{\rm cm}^{-3}$, $\gamma_{\rm osc}^{\max 2} \approx 4.8$, and $\tau_{\rm bl} \approx 157$ s. This example also corresponds to realistic values of $R_{\rm bl}$ and, in addition, to shorter $\tau_{\rm bl}$, but its use for illustration purposes seems to be undesirable due to a potential importance of the motion of ball lightning with wind.

In Ref. [17], the dependence of $S^{\rm eff}$ on photon energy for the whole 0.12–10 MeV energy range is not presented. Therefore, for this range, the calculation of the number $N_{\rm bl}$ of counts of photons from ball lightning is impossible. The estimate using the assumption $S^{\rm eff} \approx$ const yields $N_c'/N_{\rm bl} \approx 4.8 \times 10^{-2}$. For this estimate, the probability $p_{\rm d1}$ of detection of a photon with energy $\varepsilon_{\rm phot} \geqslant 0.12$ MeV, emitted by the ball lightning in an arbitrary direction, in the 0.12–10 MeV energy range was described as

$$p_{\rm d1} \approx \frac{S_l^{\rm eff}}{4\pi d^2} k_{\rm b1}(\varepsilon_{\rm phot}, d) \exp[-d/l_i(\varepsilon_{\rm phot})],$$

where $k_{\rm b1}$ is the buildup factor, taking into account the propagation of photon without scattering and its scattering without a decrease in energy lower than 0.12 MeV. The fact that its result is close to $N_c'/(N - N_l) \approx 5.4 \times 10^{-2}$ seems to support the proposed interpretation of the data from Ref. [15].

At the chosen ball lightning parameters corresponding to Eq. (5), the contribution $N_l^{\rm bl}$ of production of positrons by high-energy photons from ball lightning into $N_l$ would be about $0.17 N_l \approx 90$. This and the data from Ref. [17] mean that the main contribution into $N_l$ could be brought by the production of positrons due to the photonuclear reactions initiated by the sharp $\gamma$-ray flash accompanying the formation of ball lightning or, more definitely, the initial acceleration of electrons of its core [19]. This $\gamma$-ray flash could be generated in the region of the formation of ball lightning and/or near the head(s) of other leader(s) of ordinary lightning that created ball lightning (see also, Refs. [13,22,23,30]).

The value of $N_l^{bl}$ was calculated assuming that photons from ball lightning produced electron-positron pairs in air and concrete building roof on which the detector was placed [15] and the motion of positrons in air was not influenced significantly by thunderstorm electric fields. Parameters describing the production of the pairs in concrete and the scattering of photons in it were approximated by those of aluminum [25]. The production of the pair by photons scattered in air and the contribution of scattered annihilation photons into $N_l^{bl}$ were described with the use of the proper buildup factors. For example, the probability $p_d^{an}$ of detection of the photon of an electron-positron annihilation line after annihilation of a positron in air at the distance $d_{an}$ from the detector was described by

$$p_d^{an} \approx \frac{S_l}{2\pi d_{an}^2}(1 + 1.95 \times 10^{-5} d_{an}[\mathrm{cm}]) \times \exp(-d_{an}[\mathrm{cm}]/8989).$$

The distance between the point of production of the electron-positron pair and that of annihilation of the positron from this pair was considered negligible because, in the absence of a sufficiently strong macroscopic electric field, the typical range of the positron with $\varepsilon_k$ of several MeV and less in any matter is much less than the typical length of Compton scattering of the photon with $\varepsilon_{phot} = mc^2 \approx 0.511$ MeV in this matter [26,27,31].

## V. SOME PROBLEMS RELATED TO IDENTIFICATION OF SOURCES OF PROLONGED $\gamma$-RAY AND/OR X-RAY EMISSIONS WITH BALL LIGHTNING

Identification of a prolonged $\gamma$-ray and/or x-ray source with ball lightning will be reliable when visible light from ball lightning is recorded and/or observed visually and the possibilities of both misoperation of the detector(s) and emission of all of the high-energy photons by other source(s) are excluded. The brightness of ball lightning is usually about that of a 100–200 W incandescent lamp or less, but brighter ball lightning were also observed [32,33]. For example, Asonov reported ball lightning with diameter of about 25 cm light which was brighter than that of a 20 kW xenon lamp [32].

A search for visible light from ball lightning in the GROWTH and other experiments on a search for high-energy photons of atmospheric origin is highly desirable for both establishing the physical nature of ball lightning and estimation of its danger for, first of all, humans and aircraft (the model proposed in Ref. [8] and the observational data [2,6,8] yield that high-energy photons from some ball lightning are highly dangerous due to their biological effects and ability to cause misoperation of electronic equipment). In turn, without detection of high-energy photons, reliable identification of a flying visible radiation source, observed at a thunderstorm, with ball lightning can be difficult due to the possibility of St. Elmo's fire on flying concentrator(s) of an electric field [33–35].

The possibility of misoperation of the radiometer is the only reason that we do not conclude with confidence that the high-energy photons from ball lightning were recorded by Dmitriev [2].

The fact that the prolonged emission recorded by the GROWTH experiment on January 13, 2012 contained photons with energies above 0.6 MeV [15] means that this emission did not completely result from production of the $\beta^+$-active isotopes by the sharp $\gamma$-ray flash. However, in some situations, photons arising due to annihilation of positrons emitted by such isotopes are probably able to mask and even mimic photons from ball lightning observed in the visible range. For example, let us assume that ordinary lightning generates both ball lightning and a short $\gamma$-ray flash, which emits photons with energies sufficient for production of the $\beta^+$-active isotopes, but such photons do not reach the vicinities of the detectors due to their angular distribution (see, e.g., Refs. [30,36]) and, therefore, the signals similar to the decaying components of $R_{pr}^{count}$ described in Ref. [17] are not registered. The motion of ball lightning and the $^{13}$N and $^{15}$O isotopes with wind will be more or less similar (here it is assumed that the motion of ball lightning will not be strongly influenced by the thunderstorm electric fields), while the detected fluxes of the annihilation photons can significantly exceed those from ball lightning. First of all, generation of ball lightning and a $\gamma$-ray flash producing the $^{13}$N and $^{15}$O isotopes can occur near the heads of the different leaders of an ordinary lightning and, therefore, the typical distances between the detectors and ball lightning can be significantly longer than those between the detectors and the main region of location of the isotopes. Even when the $\gamma$-ray flash producing the $^{13}$N and $^{15}$O isotopes is generated in the region of the formation of ball lightning, at large initial values of $d$ the fluxes of photons from ball lightning in the regions of the location of the detectors can be relatively weak or even practically unobservable due to the small value of $\varepsilon_{osc}^{max\,1}$ (for example, at $\varepsilon_{osc}^{max\,1} \leqslant 300$ keV) and/or a decrease in $\varepsilon_{osc}^{max}$ during the motion of ball lightning toward the detectors. At sufficiently low $\varepsilon_{osc}^{max\,1}$, the signals similar to the decaying components of $R_{pr}^{count}$ can also mask or mimic the registration of high-energy photons from ball lightning, but revealing effects related to such signals seems to be relatively simple.

The data from Ref. [17] yield that the annihilation of positrons, emitted by the $\beta^+$-active isotopes, in flight did not bring an observable contribution into the spectrum of the prolonged emission recorded by the GROWTH experiment on February 6, 2017. However, the problem of the possibility of manifestation of the runaway of both positrons, emitted by such isotopes, and electrons and positrons, accelerated or created by photons from ball lightning, in thunderstorm electric fields [13,29] requires special studies (see also Ref. [15] where the assumption about the formation of a beam of positrons is presented). In principle, such runaway could increase $\varepsilon_{max}$ and determine, during some period, its dependence on time. The problem of the possibility of physically important motion of positrons of both origins in a thunderstorm electric field without runaway also requires special studies.

It is evident that registration of high-energy photons from ball lightning at short $d$, for example, at $d \leqslant 10$ m, is highly desirable because such registration would provide, first of all, a practically undisturbed spectrum of these photons.

According to the model proposed in Ref. [8], the upper boundary of such spectrum and its decrease with time would also provide the values of $\varepsilon_{\text{osc}}^{\max}$, $n_i$ [see Eq. (6)], and, thereby, $n_e$, while these densities and the intensity of the radiation in some spectral range would yield $V_f$ [see Eq. (2)] [9]. A comparison of $V_f$ with the visible volume of ball lightning would provide additional information about the structure of ball lightning. It seems, however, that the probability of the realization of $d$ of a few tens of meters and less will be high only in the special experiments on the formation of ball lightning. Some of the possible experiments of such a kind are described in Ref. [19]. The parameters of the ball lightning core can also be estimated when propagation of photons from ball lightning to the detector(s) is influenced by air [9], but the dependence of the accuracy of such estimates on $d$ requires special studies.

## VI. CONCLUSION

A demonstration of the possibility to explain $\varepsilon_{\max}$, $N_c{}'$, and $t_c{}'$ from Ref. [15] as parameters of radiation from ball lightning with realistic lifetime and visible radius is the main result obtained in this paper. The result of the estimate of the ratio $N_c{}'/N_{\text{bl}}$ is in accordance with the proposed interpretation of the data from Ref. [15], but the importance of its proximity to the ratio $N_c{}'/(N - N_l)$, which is supposed to be an analog of $N_c{}'/N_{\text{bl}}$, remains unclear due to the unavailability of the values of $S^{\text{eff}}$ at photon energies strongly different from 0.511 MeV.

The ball lightning model proposed in Ref. [8] and estimates presented above yield that the NaI detector used in the GROWTH experiment in 2012 was able to register the high-energy photons from ball lightning with $R_{\text{bl}} \approx 10-12$ cm from the distances up to at least about 2–2.2 km. The use of equipment for the search for visible light from ball lightning in the GROWTH experiment would provide the unique possibility to check the assumption about the emission of photons with energies of the order of 100 keV and higher by ball lightning. If this assumption is confirmed, the GROWTH experiment will be able to determine the quantitative parameters of the fluxes of such photons.

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