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High-Energetic Radiation from Gas Discharge Associated with the Maximum Rate of Current Change

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The X-ray and gamma-ray radiation was registered in the moments of the maximum speed of current change (10 kA/ns) in the gas discharge tube. The collision of relativistic electrons with Krypton (Kr) and Xenon (Xe) as with metal vapor in the plasma discharge can intensify the X-ray emission due to their bigger atomic charge. Due to the freezing of heavy water in the cloud ice particles the concentration of Deuterium in them will be significantly higher then in water vapor. The neutrons (2.45 MeV) and high energy protons (3.02 MeV) from lightning and thunderstorm can be produced in D–D nuclear fusion reactions. The high-energetic radiation from lightning and thunderstorm can be associated bought with proton capture and neutron capture. The fast neutrons should be slowdown to the thermal neutrons in the reaction of type (n, n). The photon energies in gamma-ray spectrum can rise up to 19.8 MeV. The X-ray and gamma-ray signatures from lightning can be explained due to the Compton scattering effect. The observation of the long period gamma ray radiation during the thunderstorm can be due to the decay of isotopes.

Key words and phrases: Lightning discharge, gas discharge, X-ray, gamma ray, nuclear fusion, proton capture, neutron capture, Compton scattering.

1. Introduction

The Discovery of Intense Gamma-Ray Flashes from the Earth atmosphere was done in 1994 by the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory [1]. Terrestrial gamma ray flashes (TGF) are associated with lightning activity. The source and the nature of TGFs are under discussion of space physics community up to the current date. The typical parameters of TGF seen from the orbit are fluence of ~ 1 photon/cm^2, duration of ~ 0.5 ms and photon energies can exceed 20 MeV [1,2]. Usually TGFs are associated within several milliseconds with lightning current pulses [3] or with intracloud lightning discharges [4].

The gamma ray attenuation in air from the high-altitude intracloud lightning is not so huge to detect them from space [5]. The BATSE TGFs production are at altitudes less then 20 km and at higher altitudes from 30 km to 40 km and the dispersion signatures can be explained as a pure Compton effect [6].

The neutron bursts were associated with atmospheric lightning discharges [7] and magnitude up to 10^7–10^{10} neutrons per stroke were observed [8]. Neutron production in TGFs have been observed experimentally in coincidence with lightning [9].

2. X-ray Emission

The measurements of the X-ray emission from rocket-triggered lightning was done by Dwyer, J. R., et al. [10] they conclude: "The x-rays were primarily observed to be spatially and temporally associated with the dart leaders with a possible contribution from the beginning of the return strokes, with the most intense x-ray bursts coming from the part of the lightning channel within ~ 50 m of the ground". The laboratory sparks in air was studied after that [11] and the X-ray was found from 1.5 to 2.0 m spark gap and 5–10 cm series spark gaps within the 1.5 MV Marx generator.

The similar laboratory spark discharge producing the X-ray radiation was done at the Technical University of Eindhoven in the Netherlands [12]. But the X-ray source

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and the physical mechanism of this phenomenon are still under discussion. From the video (Fig. 1) one can see the plasma turbulence in the spark discharge and the very hot point on the grounded electrode visible for more then 5 ms. This overheated point can be the emitter of the metal vapor and the electron beam due to the thermo-electron emission. The role of the thermo-electron emission for formation of fast electrons flow was experimentally investigated and X-ray radiation was found at the initial stage of the spark discharge in the atmospheric air [13]. So the X-ray radiation with the source close to the grounded electrode can be due to the collision of electron beam with atoms and ions. The metal vapor and the atoms with bigger atomic charges are more effective for X-ray production. The evaporation of the metal wire in spark discharge decrees the ionization potential and produces the heavy ions. That can explain that the X-ray bursts from rocket-triggered lightning done by Dwyer, J. R., et al. was from the altitude ~ 50 m from the ground.

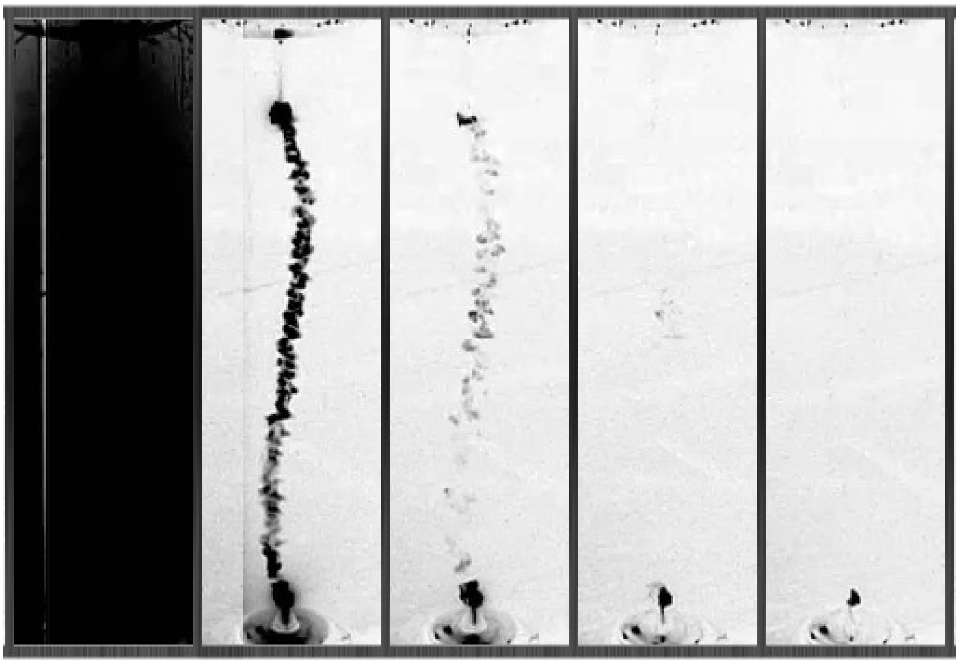

Figure 1. Plasma turbulence in the Spark discharge 1MV with 1m channel. Author's inverse color video at 1200 fps taken on the camera Casio Exlim EX-F1 in the High-voltage laboratory at the Technical University of Eindhoven in the Netherlands (28 October 2010). Courtesy to A.P.J. van Deursen and C.V. Nguyen

3. High-Energetic Radiation from Gas Discharge

The 99.99997% of the earth's atmosphere mass is concentrated below 100 km, distributed approximately as 50% is below 5.6 km and 40% from 5.6 km to 16 km. The lightning phenomenon also covers the first 100 km of the earth's atmosphere.

During the lightning discharge the air gas mixture will came in the hot plasma conditions with the temperature up to the 30000 K. Due to the stratification on low altitudes (close to the earth's surface) the current density and the plasma temperature will be the highest. The opinion exists that in this conditions the nuclear fusion reactions are impossible [14].

The lightning discharge is not a homogeneous and can consist from a big number of brunching dischargers following in the main stroke. Each stroke enter the main plasma channel inject in it huge current (10–100 kA) within some nanoseconds. The main difference from the standard theory is that the current injection goes in the plasma channel with a very good conductivity. So what we may conclude, that during the lightning discharge within a short period of time it can be modeled as continuous gas discharge with a number of high current injection in it. This is a well-known pinch effect that will significantly increase the current density and the plasma temperature within some nanoseconds, so the possibility of the nuclear fusion reactions will appear. The first public announcement on the thermonuclear reactions in gas discharge was done by I. V. Kurchatov in his Speech at AERE/Harwell on 25th April 1956 [15].

The pinch effect can create instability of continuous gas discharge; it can be due to the current oscillations that lead to the plasma density variation, or some turbulence (Fig. 1) in the hot plasma. The shock waives can appear cased by the pinch effect that can interrupt the current (within some nanoseconds) and the local breakdown will follow after that. The new strokes will enter the main plasma channel and this pinch sequence generation can follow for hundreds of times. This kind of hot plasma instability can create the plasma focus conditions in the compact area of plasma channel. The electric and magnetic fields in plasma focus are so huge that nuclear fusion reactions can go.

The X-ray emission usually observed during the pinch effect in the hot plasma conditions [15] that is very common to the parameters of lightning stroke. The electrons and ions will be accelerated in the huge electric field for the energies of some MeV, and after that collide with emitting X-ray burst together with the high energy photons. The collision of relativistic electrons with Krypton (Kr) and Xenon (Xe) in the plasma discharge can significantly intensify the X-ray emission due to their bigger atomic charge.

It looks like the Deuterium concentration is too small in the regular water for the nuclear fusion reactions. The hydrogen isotopes concentration in water is Hydrogen 99.985% and Deuterium 0.015%, so about one in 6420 Hydrogen atoms in seawater is Deuterium. About one molecule of semiheavy water HDO can be in 3210 molecules of the regular water and heavy water D_2O occurs in the proportion of one molecule in 41.2 million. The sea water evaporates from the sea surface and the water vapor rising in the atmosphere. During the cloud formation the air humidity in the cloud is close to 100% and a big amount of water is condensate in the droplets and ice particles. Due to the different freezing points of the water ($T_{\mathrm{H_2O}} = 0^\circ\mathrm{C}$) and heavy water ($T_{\mathrm{D_2O}} = 3.82^\circ\mathrm{C}$) the concentration of heavy water will be bigger in the cloud ice particles. Due to the freezing of heavy water in the cloud ice particles the concentration of Deuterium in them will be significantly higher then in water vapor. So the ice crystals in the clouds can be the perfect nuclear fuel with high concentration of heavy water.

4. Basic Equations

The D–T, D–D and D–^{3}He reactions can go with the resulting energy barrier approximately from 100 KeV. We consider the D–D reactions going with the equal probability:

$$^2_1\mathrm{H} + {}^2_1\mathrm{H} \to {}^3_2\mathrm{He}(0.82\ \mathrm{MeV}) + {}^1_0\mathrm{n}(2.45\ \mathrm{MeV}), \tag{1}$$

$$^2_1\mathrm{H} + {}^2_1\mathrm{H} \to {}^3_1\mathrm{H}(1.01\ \mathrm{MeV}) + {}^1_1\mathrm{p}(3.02\ \mathrm{MeV}). \tag{2}$$

The products of the D–D reaction can collide with Deuterium:

$$^3_1\mathrm{H} + {}^2_1\mathrm{H} \to {}^4_2\mathrm{He}(3.5\ \mathrm{MeV}) + {}^1_0\mathrm{n}(14.1\ \mathrm{MeV}), \tag{3}$$

$$^3_2\mathrm{He} + {}^2_1\mathrm{H} \to {}^4_2\mathrm{He}(3.6\ \mathrm{MeV}) + {}^1_1\mathrm{p}(14.7\ \mathrm{MeV}). \tag{4}$$

The main outputs from the D–D Fusion reaction are neutron 2.45 MeV (1) and proton 3.02 MeV (2). Due to the very low concentration of T and ^{3}He a small probability of neutron 14.1 MeV (3) and proton 14.7 MeV (4) appearances exist. On the next stage the nuclear reaction can go in two different ways. The first one is the proton capture and the second is the neutron capture reactions.

The proton capture reaction is well known nuclear reactions of type (p,γ) and (p,α), so it can affect the chemical element and isotope structure of air gas mixture.

$$
{}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \to {}^{3}_{2}\mathrm{He} + \gamma + 5.49\ \mathrm{MeV}, \tag{5}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \to {}^{4}_{2}\alpha + \gamma + 19.814\ \mathrm{MeV}, \tag{6}
$$

$$
\begin{aligned}
{}^{1}_{1}\mathrm{H} + {}^{12}_{6}\mathrm{C} &\to {}^{13}_{7}\mathrm{N} + \gamma + 1.94\ \mathrm{MeV}, \\
{}^{13}_{7}\mathrm{N} &\to {}^{13}_{6}\mathrm{C} + {}^{0}_{1}e^{+} + \nu_e + \gamma + 2.22\ \mathrm{MeV},
\end{aligned} \tag{7}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{13}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N} + \gamma + 7.55\ \mathrm{MeV}, \tag{8}
$$

$$
\begin{aligned}
{}^{1}_{1}\mathrm{H} + {}^{14}_{7}\mathrm{N} &\to {}^{15}_{8}\mathrm{O} + \gamma + 7.29\ \mathrm{MeV}, \\
{}^{15}_{8}\mathrm{O} &\to {}^{15}_{7}\mathrm{N} + {}^{0}_{1}e^{+} + \nu_e + \gamma + 2.76\ \mathrm{MeV},
\end{aligned} \tag{9}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{15}_{7}\mathrm{N} \to {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\alpha + 4.97\ \mathrm{MeV}, \tag{10}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{15}_{7}\mathrm{N} \to {}^{16}_{8}\mathrm{O} + \gamma + 12.13\ \mathrm{MeV}, \tag{11}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{16}_{8}\mathrm{O} \to {}^{17}_{9}\mathrm{F} + \gamma + 0.6\ \mathrm{MeV}, \tag{12}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{17}_{8}\mathrm{O} \to {}^{18}_{9}\mathrm{F} + \gamma + 5.61\ \mathrm{MeV}, \tag{13}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{18}_{8}\mathrm{O} \to {}^{19}_{9}\mathrm{F} + \gamma + 7.994\ \mathrm{MeV}, \tag{14}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{18}_{8}\mathrm{O} \to {}^{15}_{7}\mathrm{N} + {}^{4}_{2}\alpha + 3.98\ \mathrm{MeV}. \tag{15}
$$

The isotopes of Cl, K, F, Na, Br, Rb, I, Cs can appear in the proton capture reactions with Ar, Ne, Kr, Xe.

$$
{}^{1}_{1}\mathrm{H} + {}^{A}_{Z}\mathrm{X} \to {}^{A+1}_{Z+1}\mathrm{X} + \gamma, \tag{16}
$$

$$
{}^{1}_{1}\mathrm{H} + {}^{A}_{Z}\mathrm{X} \to {}^{A-3}_{Z-1}\mathrm{X} + {}^{4}_{2}\alpha\,. \tag{17}
$$

The neutron capture can go in reactions of type (n,n), (n,γ), (n,p), (n,α), $(n,2n)$.

The absorption cross section is often highly dependent on neutron energy. So the fast neutrons (2.45 MeV) should be slowdown to the thermal neutrons in the reaction (18). In the wet air it is possible due to the reaction of type (n,n) on the atoms of Hydrogen $\left({}^{1}_{1}\mathrm{H}\right)$, Carbon $\left({}^{12}_{6}\mathrm{C}\right)$, Nitrogen $\left({}^{14}_{7}\mathrm{N}\right)$, and Oxygen $\left({}^{16}_{8}\mathrm{O}\right)$.

$$
{}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} \to {}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n}\,. \tag{18}
$$

After that for the thermal neutrons are used, the process is called thermal capture. This reaction of type (n,γ) (19) can go on Helium $\left({}^{3}_{2}\mathrm{He}\right)$, Krypton $\left({}^{A}_{36}\mathrm{Kr}\right)$, Xenon $\left({}^{A}_{54}\mathrm{Xe}\right)$ and others isotopes with huge absorption cross section.

$$
{}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} \to {}^{A+1}_{Z}\mathrm{X} + \gamma. \tag{19}
$$

Xenon-135 is a perfect neutron absorber (20) due to its huge cross section for thermal neutrons $2.65 \cdot 10^{+6}$ barns.

$$
{}^{135}_{54}\mathrm{Xe} + {}^{1}_{0}\mathrm{n} \to {}^{136}_{54}\mathrm{Xe} + \gamma \ (\sigma = 2.65 \cdot 10^{+6}\ \text{barns}). \tag{20}
$$

The reaction of type (n,p) goes with proton emitting (21).

$$
{}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} \to {}^{A}_{Z-1}\mathrm{X} + {}^{1}_{1}\mathrm{p}\,. \tag{21}
$$

The examples of this reaction of type (n, p) can be the Tritium (22) and Carbon-14 (23) production.

$$ {}^{1}_{0}\mathrm{n} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p} + 0.76\ \mathrm{MeV}\ (\sigma = 5400\ \text{barns}), \tag{22} $$

$$ \begin{gathered} {}^{1}_{0}\mathrm{n} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{p} + 0.63\ \mathrm{MeV}\ (\sigma = 1.75\ \text{barns}), \\ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{1}e^{-} + \overline{\nu}_{e} + 156.47\ \mathrm{KeV}. \end{gathered} \tag{23} $$

Carbon-14 is produced (23) in the upper layers of the troposphere and the stratosphere on the altitudes from 9 to 15 km by thermal neutrons absorbed by Nitrogen-14 atoms [16]. This altitude is very common to the intracloud lightning discharges and X-rays from them [4]. The Carbon-14 production rates vary because of changes to the cosmic ray flux and due to variations in the Earth's magnetic field and had not agreed with high geomagnetic latitudes models [16]. So the variations in the lightning activity and neutron generation from them can help in estimation of global Carbon-14 budget.

The reaction of type (n, α) goes with emitting of α-particle (${}^{4}_{2}\mathrm{He}$ nucleus) (24).

$$ {}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{A-3}_{Z-2}\mathrm{X} + {}^{4}_{2}\alpha\,. \tag{24} $$

The reaction of type $(n, 2n)$ goes with emitting of two neutrons (25).

$$ {}^{A}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{A-1}_{Z}\mathrm{X} + {}^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n}\,. \tag{25} $$

So these nuclear reactions can explain the producing of the radioactive materials, gamma ray radiation and the air ionization during the lightning discharges within the thunderstorm. The photon energies in gamma-ray spectrum can rise up to 19.8 MeV and the thermal neutrons will observed. The X-ray and gamma-ray signatures can be explained due to the Compton scattering effect. The observation of the long period gamma ray radiation during the thunderstorm can be due to the decay of isotopes.

5. Experiment

The main idea of this experiment was the laboratory scale model of continuous lightning discharge with a big number of brunching dischargers following in the main stroke. The experimental model was done as the continuous gas discharge with a series of high current injection in it. So the main parameter of the experiment was the current change and the applied voltage was the source for creating the necessary form of the current in the gas discharge. During the experiment in the quartz gas discharge tube the maximum speed of current change was 10 kA/ns, the pulse repetition 1000 per second and pulse package duration up to 10 s. This huge current can create the conditions for pinch effect that will significantly increase the current density and the plasma temperature within some nanoseconds. The role of Xenon, Krypton and water vapor influence on high energy photon generation in the gas discharge was studied. The idea of this experiment was formed in 1990 and it was done in 1991. Due to the intensive X-ray and gamma-ray burst during the high current injection in plasma the experiments was discontinued.

Experiments were done in flow quartz gas discharge tube with the molybdenum electrodes. The molybdenum was chosen due to its low cross section for thermal neutrons and the sixth-highest melting point of 2890 K and evaporation temperature 4885 K. The low cross section for thermal neutrons will reduce the level of gamma-ray radiation from electrodes and the huge melting point will reduce the possibility of thermo-electron emission. The gas pressure was variable from 0.1 to 4 atm. The tube size depends from gas mixture and was: internal diameter from 2 to 7 mm; length from 50 to 100 mm; wall thickness — 2 or 3 mm. During the experiments some tubs were destroyed and the tube size changed. The gas mixture was different from dry and wet air up to it components: xenon, krypton, nitrogen, carbon dioxide and water vapor. The most stable gas discharge was in the xenon atmosphere (pressure 1.28 atm), tube geometry: internal diameter 7 mm; length 80 mm; wall thickness — 1.5 mm. The water vapor can be easily added in gas discharge by injecting some portion of pure water in the tube.

The ionization potential of pure water (H_2O — 12.62 eV) and Xenon (Xe — 12.13 eV) are the lowest in the air mixture. So the air ionization potential will be close to the lowest component in the mixture. The main reason for using the Xenon with pure water in gas discharge was the minimization of continuous current and increasing the length of gas discharge. The main reason of tubes explosions was the huge continuous current in other gases. The Xenon presence in the gas discharge reduced the continuous current for the value of less then one Ampere and the maximum peak current exceeded it at 10^5 times. The current measurement was done in the coaxial section of ground electrode with a current probe. So the achieved parameters of gas discharge were: continuous current less then 1 A; current pulse rising speed 10 kA/ns; current pulse duration from 100 ns till 1 μs; pulse repetition frequency from 1 to 1000 Hz; pulse package duration from 1 up to 10 s.

During the experiments the scintillator counter NaI(Tl) registered the bursts of ionizing radiation on the pulse repetition frequency. After that the measures for the proper X-ray and gamma-ray detection were done.

The near electrode space (cathode and anode) of the gas discharge tube were shielded by lead, 20 mm thick. So the simple collimator was done to protect the detectors from X-ray radiation going from near electrode space.

The two detector units were installed close to the gas discharge tube in the metal boxes with the aluminium (Al) windows 50 or 100 μm thick.

The first one was the spectroscopic scintillator detector NaI(Tl) (diameter 30 mm on 40 mm size) with PMT. The calibration was performed by using the known photon energies of the isotopes Cobalt-60 (Decay energy = 2.824 MeV) and Yttrium-88 (Decay energy = 1.83 MeV).

The second — was the 4 independent Geiger Müller counters SBM-19 with independent pulse discriminators combined in pairs with coincidence circuit. Each of them was in one plane with gas discharge tube so the particle passing through both counters will be detected.

The detector system was protected from the electromagnetic interference so the current pulse through the metal wire does not provide any counts.

The current and scintillator detector signals was observed on two-channel analog oscilloscope C1-104 with the frequency band 500 MHz and rising time from the level 0.1 to 0.9 within 0.7 ns.

The X-ray and gamma-ray radiation was registered in the moments of the maximum speed of current change (10 kA/ns) in the gas discharge tube. During the X-ray and gamma-ray bursts the scintillator detector was usually saturated and it was impossible to estimate the photon energy from the signal level. The group of high energy photons coming within the response time of the NaI(Tl) scintillator provide a huge flash proportional to the total energy of all registered photons. Variation of the aluminium window thick in front of the detectors does not influence the counts.

Only in the second channel with pair of Geiger Müller counters and coincidence circuit it was possible to detect the gamma-rays. It is important to underline that this simultaneous counts is the independent confirmation of the generation of gamma-ray photons during the current pulses in gas discharge tube.

Taking into account the detectors time delay the moment of maximum speed of current variation was associated with the X-ray and gamma-ray burst.

For the proper control of D–D reactions and possible neutrons generation it is very important to add in the experimental equipment the neutron detector. For shielding the personal from the ionizing radiation it is important to provide it with neutron slowed down and neutron absorber layers after that the gamma-ray protection will be necessary.

6. Discussion

X-ray and gamma-ray bursts with neutrons appear not in every lightning discharge, they are rare in CG lightning and usually associated with intracloud lightning where the high pulse repetition rate can be observed. It is possible to explain this phenomenon by pinch effect or hot plasma instability with the plasma focus conditions in the compact area of plasma channel. The conditions for the pinch effect can be only in the case when the next lightning discharge goes in the same channel during the continuous current stage. For the intracloud lightning the repetition rate can go up to some hundreds within $\sim 100\ \mu$s, so the pinch effect can be common for them. The CG lightning usually goes with lower rate of some events per second and choosing the new channel for the next stroke. But it can happen that CG lightning goes in the same channel within some ms twice. So for the CG lightning the probability of pinch effect is lower then for intracloud lightning. This fact can explain that a few CG lightning can produce X-rays and gamma-rays with neutrons and for the intracloud lightning the high energy photons and neutrons are common.

The production of neutrons 2.45 MeV and protons 3.02 MeV in D–D Fusion reaction together with proton capture and neutron capture reactions can explain the production of the radioactive materials, gamma-ray radiation and the air ionization during the lightning discharges within a thunderstorm. The role of Helium (^{3}He), Krypton (Kr), Xenon (Xe) and others isotopes with huge absorption cross section is significant for the thermal neutrons capture. The X-ray and gamma-ray signatures from lightning can be explained due to the Compton scattering effect. The observation of the long period gamma-ray radiation during the thunderstorm can be due to the decay of isotopes.

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Излучение фотонов высокой энергии в газовом разряде, ассоциированное с моментом максимальной скорости изменения тока

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Рентгеновское и гамма излучение были обнаружены в моменты максимальной скорости изменения тока (10 kA/ns) в газовом разряде. Столкновение релятивистских электронов с ядрами криптона (Kr) и ксенона (Xe), а также с атомами паров металлов в разряде плазмы могут существенно усилить рентгеновское излучение благодаря большому заряду ядер этих атомов. Благодаря замерзанию дейтерия в кристаллах льда в облаках концентрация дейтерия в них будет существенно выше, чем в водяном паре. Нейтроны (2,45 МэВ) и протоны (3,02 МэВ) высоких энергий из разрядов молний могут быть получены в D–D ядерных реакциях синтеза. Фотоны высоких энергий от молний могут быть ассоциированы с реакциями захвата нейтронов и протонов. Быстрые нейтроны замедляются до тепловых в реакциях типа (n, n). Энергии фотонов в спектре гамма излучения от молний могут достигать 19,8 МэВ. Особенности рентгеновского и гамма спектров от молний могут быть объяснены эффектом Комптона. Наблюдение длительного гамма излучения во время гроз может быть объяснено благодаря распаду короткоживущих изотопов.

Ключевые слова: разряд молнии, газовый разряд, рентгеновское излучение, гамма излучение, реакции ядерного синтеза, захват протонов, захват нейтронов, эффект Комптона.