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Electromagnetic Induction and Relativistic Double Layer: Mechanism for Ball Lightning Formation †

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Abstract: What is the probability that ball lightning (BL) is a real phenomenon of nature? The answer depends on your *prior information*. If you are one of those lucky men who had a close encounter with a BL and escaped unscathed, your probability that it is real equals, of course, unity. On the other hand, if you are a theoretical physicist deeply involved in the problem of controlled thermonuclear fusion, your probability is likely to be zero. In this study, an attempt is being made to raise the likelihood of reality of BL phenomenon for everyone, plasma physicists included. BL is conceived here as highly structured formation of air, at roughly atmospheric pressure, with a set of nested sheaths, each of which is a double electrical layer with voltage drop in the order of 100 kV.

Keywords: prior information; ball lightning; fireball; bead lightning; double electrical layer; dynamic capacitor; controlled nuclear fusion

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1. Introduction

Ball lightning, or *fireball*, is an atmospheric phenomenon in the form of a long-lived luminous sphere. Floating slowly in the air, or hovering over the ground, BL is observed most frequently in close proximity of a lightning strike during intense thunderstorm activity. There are numerous eyewitness accounts from around the world that are quite consistent with each other. This fact alone is a strong evidence for the reality of this phenomenon. Nevertheless, the reported characteristics and features of BL appear not only contradictory, but seem to be at odds with the well-established laws of nature, which makes it hard for some down-to-earth physicists to take the reality of this phenomenon seriously. The most puzzling feature of BL is its longevity—it can last for seconds to minutes. At the same time, it is the most obvious and undeniable attribute of BL. It was the longevity of BL that made the Nobel Prize winning physicist Pyotr Kapitsa to draw the following conclusion [1]:

> Since the energy stored in the cloud [of nuclear detonation] is proportional to the volume d^3, and the emission of the surface is $\sim d^2$, energy radiation from the ball will last for time interval proportional to d, its linear size. The mushroom cloud of a nuclear explosion with a diameter d of 150 m lasts for less than 10 s, so the energy of a ball with a diameter of 10 cm shall be exhausted in less than 0.01 s. But in fact, as indicated in the literature, ball lightning of this size most often lives for a few seconds, sometimes even a minute. Thus, if there are no sources of energy in nature not yet known to us, due to the law of conservation of energy we have to accept that energy is continuously supplied to ball lightning as long as it glows, and we are forced to look for this source of energy outside the body of ball lightning.

Kapitsa suggested that the external source of energy for BL is a short-wave radio emission in the 35 to 70 cm range, and that the presence of ionized air facilitates the creation of radio waves, while the causative agent of these oscillations is the strike of a thunderbolt. However, despite numerous attempts, no one ever succeeded in detecting the indicated radio emission.

If we are to assert that the energy of BL is self-contained, we are confronted with a baffling feature of BL in the form of incredibly high density of energy content. Based on eyewitness reports, the energy content of most fireballs must be in the order of 10 or 100 kJ. However, a few sightings were reported in the literature which suggests that the energy of a fireball can be as high as 10 MJ or even higher. The most widely known evidence for the possibility of extraordinary high density of energy stockpiled in a BL is the publication in *The Daily Mail* on Nov 5, 1936 of a letter to the editor from one Mr. W. Morris with a title *A thunderstorm mystery* [2]:

> Sir, during a thunderstorm I saw a large, red hot ball come down from the sky. It struck our house, cut the telephone wires, burnt the window frame, and then buried itself in a tub of water which was underneath. The water boiled for some minutes afterwards, but when it was cool enough for me to search I could find nothing in it...

Specific heat of water is about 4 200 J/kg·K, so, if water in the amount of 18 liters (four British gallons, as indicated in the letter) was heated from, say, 20° C to the boiling point of 100° C, it follows that the energy of the BL was over 6 MJ. To visualize the enormity of this energy for a small globular object of 10 cm in diameter, which is capable of hovering freely over the ground, suffice to note that it matches the kinetic energy of a 5-ton truck dashing at 176 km/h! Just think of the destructive power of this "bullet". Is it possible to fit somehow that much energy in a luminous ball of air weighing less than one gram? For instance, what temperature is required in order to dissociate all the N_2 and O_2 molecules in one gram of air, then singly ionize all nitrogen and oxygen atoms, and, finally, bring the thermal energy of the resulting plasma to 6 MJ? Simple calculations point to a temperature of nearly $4,000,000°$ K. Yet, according to eyewitness reports, BL does not produce a marked sensation of heat at arm's length or even closer!

Kapitsa's assertion about the source of BL energy being outside its body is based on the premise that fireball is nothing but a fully ionized air, i.e., a regular plasma. So, it overlooks the idea that the energy in question could be, quite simply, ordinary kinetic energy of ultrarelativistic electrons, the motion of which is *coordinated* in some intricate way at the inception of a fireball. In other words, perhaps BL is not your ordinary plasma, but rather a *highly structured* object comprised of both neutral and charged particles. Nurbey Gulia, the inventor of the so-called *superflywheel*, disagrees with the main thesis of Kapitsa that the source of energy in BL is to be sought outside its body. He gives a number of compelling objections to the model in general, and then proceeds to suggest that BL is a kind of plasma flywheel created by nature itself [3]. And that is precisely what we hope to demonstrate on the following pages, concluding with a fairly detailed experimental schema for creating fireballs in a lab to test the idea. But our "fire flywheel" will differ profoundly from its mechanical cousin.

2. In Search for a Mechanism of High Energy Accumulation in BL

Consider an annular glass tube of small cross-section. The tube is evacuated to a high vacuum, and there is a free electron inside it that can slide along the tube with no friction. Suppose there is a magnetic field, which is orthogonal to the plane of the ring and distributed uniformly through space. Let the magnetic induction rise from zero to $B_a = 1.5$ T (magnetic field in the vicinity of lightning discharge channel can reach this level). How much energy will our free electron acquire? Electron's motion is determined by the second law of motion and the law of electromagnetic induction:

$$eE_{vrtx} = \frac{\mathrm{d}\,p}{\mathrm{d}\,t}, \qquad 2\pi R E_{vrtx} = \frac{\mathrm{d}(\pi R^2 B)}{\mathrm{d}\,t},$$

where e and p are electron's charge and momentum, respectively, E_{vrtx} is a vortex electric field, and R is the radius of the ring. With the assumption that the electron was initially at rest, this yields

$$p = \frac{eRB}{2}. \tag{1}$$

Now, recalling the relationship between the momentum and the energy of relativistic particles, $(m_0c^2)^2 + (pc)^2 = E^2$, for the kinetic energy of the electron at the height of its acceleration we have:

$$K = E - m_0c^2 = (\sqrt{1+\alpha^2} - 1)m_0c^2, \text{ where } \alpha \equiv \frac{eRB_a}{2m_0c}. \tag{2}$$

Substituting $R = 0.05$ m and $B_a = 1.5$ T into this equation, we get $K = 10.7$ MeV. That is, our electron accumulates kinetic energy in the amount comparable to that of deuteron-triton fusion event, 17.6 MeV! This estimate is based on idealized and simplified schema, of course. Nevertheless, the fact that the vortex electric field, which is generated by a lightning discharge, is capable of accelerating a nearby free electron to ultrarelativistic velocities gives us a real hope of understanding how a BL accumulates enormous amount of energy at its inception. Indeed, all is left to do is to demonstrate that, starting with a few random seed electrons, electromagnetic induction can cause an avalanche ionization in the air and accelerate not one, but many electrons, forming in the process a stable configuration of charge particles. This is easier said than done, but we shall give it a try.

The idea of vortex field as the mechanism behind charging BL with energy at its birth is not entirely new [4]. The betatron model has a serious difficulty though, which boils down to the following. While the magnetic flux through a hypothetical vacuum ring is rising, the electron gains in speed and energy, but when this flux inevitably subsides and vanishes, the electron's speed shall fall back to its original value. That is precisely why electrons must be moved out of the betatron's vacuum chamber as soon as the magnetic flux is peaked. But how does nature prevent electrons from losing all the acquired energy when acceleration turns inevitably to deceleration? We won't find an answer to this question in [4] for it is not even raised there. We'll postpone this question for now and answer it later.

Let's try to imagine in outline how fireballs are created in nature. Consider lightning discharge channel as a long straight tube—horizontal when lightning bolt strikes between the clouds, or vertical when lightning hits the ground. It takes only a few microseconds for the discharge current to reach its peak value ~ 100 kA. Rapidly rising electric current generates a rapidly rising magnetic flux around the streamline. Let the diameter of the discharge channel be $d = 5$ cm, while the amplitude of the current $I_a = 200$ kA. Magnetic induction around the discharge channel has its peak value at the surface of the channel,

$$B_a = \frac{\mu_0 I_a}{\pi d} = \frac{4\pi 10^{-7} \cdot 2 \cdot 10^5}{0.05\pi} = 1.6 \text{ T}.$$

Consider now a thick toroid, which is tightly embracing the discharge channel. Magnetic field line at any point inside the toroid is perpendicular then to the toroid's cross-section at that point, so we have an intense magnetic flux along the toroid's central line. Suppose a free electron has appeared on the surface of our toroid, and let its frictionless motion be restricted to that surface. Assuming that it was initially at rest, the electron will be spun by a vortex electric field along the perimeter of toroid's cross-section. Assume now that we have not just one, but many such electrons. Then, neglecting the interaction of electrons with each other, each electron will be spun along a poloidal circle, and we'll get a BL in the shape of a... doughnut. We've been looking for a *fireball*, but have found a *firebagel* instead—what a bad luck!

But have we? Even if we get a bagel-shaped glowing object, being highly unstable, it will quickly disintegrate into a few pieces. But why wouldn't it be stable? After all, we know that skillful smokers can easily launch stable rings of smoke into the air, and the rings created by dolphins in the water are so stable that one can play with them as with elastic balls. Why then the ring of electrons rotating rapidly along the poloidal tracks on the bagel's surface is lacking topological stability? Well, because the forces that act between these charge particles are quite different—in both nature and scale—from the forces acting between electrically neutral molecules that make up rings created in the water or in the air. Indeed, parallel currents attract each other while anti-parallel currents repel. So, each individual poloidal turn of current tends to expand in the radial direction while the adjacent turns of current attract each other. Such a configuration is, obviously, highly unstable and the slightest violation of symmetry will lead to local constrictions in the bagel, splitting it into several pieces. Perhaps this is how the *bead lightning* is formed—a phenomenon of nature which is even more rare than BL.

At this stage of idealization, where we have extended the freedom of motion of charge particles to the surface of a torus, we are moving away from the betatron model. Electron flux in the betatron is highly rarefied, so ignoring the interaction between the individual charges while deriving the condition of keeping each electron in a *fixed circular* orbit—the so called Widerøe's condition—is quite justified. But the density of charges that is required to form BL is so high that the interaction between the charges cannot be ignored: electric and magnetic forces, as well as direct collisions of charge particles, will alter the trajectory of each particle in unpredictable way. Consequently, each electron is losing its circular orbit and engaging in a complicated pattern of motion, in both poloidal and toroidal directions. That's why the energy, which the electrons gain at the stage of acceleration by the vortex field, cannot be taken away entirely from them when the field changes its direction and deceleration sets in. Indeed, part of the kinetic energy of accelerated electron has already been passed to the *toroidal* component of its velocity, and this part cannot be taken away from it while decelerating in the *poloidal* direction.

3. Field Emission and Balance of Forces

Imagine a smooth ball made of highly conductive material—copper, for example—in the air. How many excess electrons can hold this ball? It can be charged until the field strength on the surface of the ball has reached the threshold value of 30 kV/cm, at which point air breakdown is triggered. If the ball is in a vacuum, there is no medium for the electrical breakdown to take place in. Nevertheless, the force of electrostatic repulsion of excess electrons, crowded in a thin surface layer on the ball, will become unbearable at some point, and they'll start leaving the ball in a hurry. This phenomenon is called *field emission*. In close to ideal vacuum conditions, field emission won't commence until the field strength on the smooth surface of the ball rises to $\sim 10^9$ V/m.

How thin is the thin surface layer, where excess electrons keep crowding until they decide that this injustice can no longer be tolerated? And why do they show such longanimity in the first place—why don't they simply run away as soon as we start charging our ball? After all, it seems there are no forces opposing the electrostatic repulsion of excess electrons cramped on the surface of the ball. And, yes, they have gathered there precisely because there are no forces inside the ball to counter their mutual dislike for each other. But as soon as the electrons reach the surface, they—for some mysterious reason—wilt as if an invisible, but very powerful barrier had sprung in front of them. Perhaps these questions may sound childish to some. But a child may ask such a simple question that no adult can answer sensibly. And how do adults answer these childish questions? They say that field emission is a quantum-mechanical effect, refer the inquiring child to the Fowler-Nordheim equation, solving of which—they add—is a highly complicated task. This "explanation" is not particularly illuminating and, frankly, hardly it can convince an electrical engineer or your ordinary physicist.

The retention of free charges on the surface of a conducting body cannot be explained if one assumes that charge carriers are really at rest on the surface of electrified body. In fact, these carriers—electrons in our case—are surely not at rest; they zip around at an average speed of $\sqrt{3kT/me}$, which is a whopping 100 km/s at room temperature! And when one of the electrons tries to escape from the crowded company of his brothers, it provokes an instantaneous rearrangement of its neighbors, which is equivalent to the appearance of a virtual mirror charge, resulting in immediate suppression of the attempt to escape. That is, the origin of forces, which hold excess electrons on the surface of a conductor, is of purely *dynamic* nature. The mirror-charge mechanism is, in my opinion, the clearest and most convincing explanation for the obstacle that prevents electrons from leaving a negatively charged conducting body. Anyhow, the fact remains whether we can explain it or not: an enormous amount of excess charge can stay on the surface of a conductor in *electrically* equilibrium state, i.e., the carriers of these charges can neither penetrate into the conductor nor escape from it. As the result of this, we get an *electrostatic* charge distribution on the surface of the conductor, and this is the most important thing for us in the whole story.

Suppose we charge our copper ball positively now, i.e., we take electrons from it instead of adding. Then we won't get electron emission, of course, but when a certain level of field strength is reached, the emission of positive ions commence. This level is of the same order as for the electron field emission, i.e., 10^9 V/m. Imagine now that we launch an electron into a circular orbit around the copper ball charged positively to the limit. How much energy this "sputnik" must have in order to stay in the orbit? Let E_s stand for the electric field strength on the surface of the ball. Then electron's motion in the orbit is described by the following equation

$$eE_s = \frac{K}{R}\left(1+\sqrt{1-\frac{v^2}{c^2}}\right), \text{ i.e. } \quad K = \frac{eE_sR}{\mu}, \tag{3}$$

where K and v are electron's kinetic energy and its velocity, respectively; $\mu \equiv 1+\sqrt{1-\frac{v^2}{c^2}}$ is a factor that varies in narrow limits ($1 < \mu < 2$).

Let $E_s = 10^9$ V/m, then the energy required for the electron to stay in a circular orbit of radius 5 cm is about 50 MeV. The orbiting electron is losing energy to synchrotron radiation. How long will it take for our electron to lose 90% of its initial energy, i.e., for its energy to fall from 50 MeV to 5 MeV? The intensity of synchrotron radiation for ultrarelativistic electrons ($\gamma \equiv E/m_0c^2 \gg 1$) is given by [5]:

$$W = \frac{ce^2\gamma^4}{6\pi\epsilon_0 R^2}. \tag{4}$$

So, the time interval, which takes γ to fall from γ_1 to γ_2, is

$$\tau = -\int_{\gamma_1}^{\gamma_2}\frac{dE}{W} = \frac{2\pi\epsilon_0 R^2 m_0 c}{e^2}\left(\frac{1}{\gamma_2^3}-\frac{1}{\gamma_1^3}\right). \tag{5}$$

Recalling that electron's rest energy is 0.51 MeV, and substituting $\gamma_1 = 100, \gamma_2 = 10, R = 0.05$ m into this equation, we get $\tau = 50$ s, which is of the right order for the lifespan of fireballs.

To accelerate an electron to 50 MeV via the mechanism of electromagnetic induction in one shot, so to speak, the required change of magnetic flux is so large that it is apparently beyond the ability of the most powerful lightning bolt. However, it should be remembered that the lightning discharge takes place in several steps of rapid succession. There are several direct and return strikes along the path laid by the leader, and each of these surges of current can charge BL with energy. We have estimated earlier that a one-time surge of magnetic induction from zero to a peak value of 1.5 T can spin up electron to 10.7 MeV. So, due to cumulative effect of direct and reverse strikes of lightning, the vortex field can accelerate electrons up to 50 MeV. From the moment of fireball's inception to the point when it catches casual observer's attention, at least a few seconds shall pass. So, it is highly unlikely that the energy of the fastest electrons in any BL to exceed a few dozen MeV. Indeed, even if we assume that an electron with a next to impossible value of 300 MeV (betatron limit) is present in a BL at its inception, it would take only a fraction of a second for its energy to fall to 50 MeV due to synchrotron radiation.

Imagine now that we have launched not one, but a whole lot of electrons along various geodesic lines, which are distributed uniformly all over our copper ball. Assume that this cloud of electrons is confined to a spherical shell of thickness h. Due to shielding of positively charged "core" by negative electron cloud, the energy of each electron is determined then by its position in the cloud—the lower the electron orbit the higher its energy. As you have probably guessed by now, huge amounts of energy can be accumulated in systems like this. Moreover, in terms of force balance, this system forms a completely legitimate and stable configuration. Note also that, in addition to the net kinetic energy of electrons, a certain amount of electrostatic energy is accumulated in this *dynamic capacitor*. Let's see which component—the net kinetic energy of electrons or the electrostatic energy of the capacitor—makes greater contribution to the stockpile of energy accumulated in this system.

Suppose a ball, with a uniform distribution of positive charges, σ, on its surface, is surrounded by a cloud of electrons orbiting the ball. Let the orbits of electrons lie within a thin shell of thickness $h \ll R$, directly above the surface of the ball, and let, finally, the density of electron distribution be a function of the height of the orbit only: $n = n(x)$. The system as a whole might be electrically neutral, or it may have an excess *positive* charge. Consider the neutral case,

$$\int_0^h en(x)\,\mathrm{d}\,x = \sigma. \tag{6}$$

Due to the assumed symmetry, magnetic forces cancel out. Then, neglecting at this point the possible collisions of electrons, the motion of each electron is determined by play of two opposing forces—the centripetal force of electrostatic attraction to the positive ball and the centrifugal force of inertia:

$$\frac{e}{\epsilon_0}\left(\sigma - \int_0^x en(x)\,\mathrm{d}\,x\right) = \frac{\mu K(x)}{R}, \tag{7}$$

where $K(x)$ is electron's kinetic energy in the orbit of hight x; μ is a function of electron's speed that varies, as noted above, in narrow limits. Therefore, when calculating the net kinetic energy K_Σ of electrons, μ can be treated as a constant with some effective value, $1 < \mu_{eff} < 2$:

$$K_\Sigma = 4\pi R^2 \int_0^h n(x)K(x)\,\mathrm{d}\,x = \frac{4\pi R^3}{\mu_{eff}\epsilon_0}\left[\int_0^h \left(\sigma - \int_0^x en(x)\,\mathrm{d}\,x\right) en(x)\,\mathrm{d}\,x\right] = \frac{2\pi R^3 \sigma^2}{\mu_{eff}\epsilon_0}.$$

We have obtained an interesting result: with a fixed R, the total kinetic energy of electrons depends only on the integral of the density function $n(x)$, i.e. the details of this function, which are not known, do not matter. Since the field strength on the surface of the ball $E_s = \sigma/\epsilon_0$, we may right this result as:

$$K_\Sigma = \frac{2\pi\epsilon_0 R^3 E_s^2}{\mu_{eff}}. \tag{8}$$

Let $E_s = 5 \times 10^9$ V/m, then for a ball of radius $R = 0.05$ m we get $K_\Sigma \approx 0.6$ MJ. The exact value of electrostatic energy, E_c, of this system depends, of course, on the details of the density function $n(x)$; regardless, it makes only a small fraction of the energy stored in the system:

$$E_c < 4\pi R^2 h(\epsilon_0 E_s^2/2) = \mu_{eff} K_\Sigma (h/R) \ll K_\Sigma. \tag{9}$$

Imagine now that our positively charged copper ball, with a cloud of electrons rapidly revolving around it, is placed inside a copper spherical shell of thickness 1 mm or less. This copper shell won't "feel" the presence of electrically neutral copper ball inside it. So, we can repeat our trick and build another double layer on the outer surface of this shell. Building up this "matreshka doll" by adding more and more copper shells to it, we can get a compact and highly dense energy storage system with a capacity in the order of 10 MJ or even higher.

But what is the relevance of this all to the phenomenon of BL? We have demonstrated the feasibility of large-orange-size material object with seemingly fantastic properties that some fireballs have according to eyewitness accounts: long life, incredibly high energy content, and low temperature. True, our "object" is heavier than air, thus it cannot hover over the ground like a fireball. To turn our copper-electronic battery into a real fireball, we need to show that a similar structure can be created from... a thin air, literally. In the design of our energy capsule above, a double electrical layer was the key element, which we have imagined rather than built in practice, while double layer sheath is a real attribute of plasma. Moreover, this attribute is created naturally by plasma itself as a way of protection from the environment. So, the transition from an imaginary double layer on the surface of a copper ball to a natural double layer in the air shall not come as a miracle to us.

With the transition from a copper ball to a ball of air, we no longer have free electrons and lose the conductivity associated with them, so it seems that the entire construct is collapsing. However, in the air—especially, in thunderstorm conditions—a small count of free electrons is always present. We have seen earlier that, with each strike of a thunderbolt, a rapidly rising flux of magnetic induction takes place around the discharge channel, thereby creating an intense vortex field. Seed electrons, which happen to be in the area of this strong field, get accelerated to energies that might be high enough to cause an avalanche ionization. At the same time, electrons—in virtue of their greater mobility—gain quickly in tangential velocity, with a tendency to scatter in radial directions due to the combined action of centrifugal force of inertia and the Lorentz force, thus leaving behind the heavy and sluggish positive ions and creating a gap in the air in the form of a thin sheath. This peculiar *rupture* in the air *is* a relativistic double layer, with an almost perfect vacuum and high intensity electrostatic field between the oppositely charged layers. It is precisely this electrostatic field that prevents electrons from scattering and confines them to the double layer sheath. This mechanism will, most likely, lead to stratification, i.e. to formation not just one, but a set of nested sheaths.

The occasional collisions of electrons in the sheaths will result in continuous ejection of highly energetic electrons from the fireball at various angles. These eruptions may manifest themselves as tiny crackling flashes of electric discharge all over the surface of BL, which can account for the "boiling" ("hairy") appearance of fireball in eyewitness reports. Besides, the electron ejections result in fireball becoming periodically net positive then neutral by attracting electrons back from the surrounding air, which is quite consistent with the erratic and highly unpredictable motion of the fireball due to electromagnetic interaction with the earth at large and metal objects in particular.

4. Schema for Creating BL in a Modestly Equipped Laboratory

The above ideas of the mechanism of BL formation suggest a schema for generating fireballs in a lab. Basically, it is as follows. In a small volume of air, create a powerful flux of magnetic induction, which peaks in a matter of a few dozen microseconds. To implement it successfully, the schema must be fleshed out, of course, with a multitude of important details.

First and foremost, experiments shall be conducted in a vessel with an air rarefied to about 1 mbar. An avalanche ionization, which—according to our model—is a requisite for creating a fireball, is much easier to trigger in a rarefied air. If we succeed in creating relativistic double layers in a rarefied air, pressure in the vessel can be raised back to atmospheric by leaking air slowly into it.

The next detail is concerned with the shape of the vessel. A hollow torus with external and internal diameters of 25 and 5 cm, respectively, might be the right choice. By passing a powerful pulse of current through a toroidal coil with a few turns of a thick rod, tightly embracing the torus, one can hope to get a few fireballs at once. To keep the coil inductance low, the number of turns of the coil shall be restricted to six. The vessel is to be made of a transparent dielectric, so one can observe what is happening inside it. An alternative choice for the vessel is a spherical glass bulb, 10 cm in diameter.

Now on the details of pulse discharge, which is to simulate the lightning bolt. This can be achieved with special, heavy duty pulse capacitors of small inductance equipped with a remotely controlled spark gap. If the vessel of choice is a spherical bulb, we need two capacitors to be discharged synchronously via two horseshoe-like copper bars. The diameter of the horseshoe must be slightly less than the diameter of the bulb. The horseshoe bars shall be located in two vertical planes, parallel to each other, on opposite sides of the bulb in a symmetrical configuration, so that the centers of the horseshoes and the center of the spherical bulb lie on the same horizontal line, while the distance between the centers of the horseshoes is slightly larger than the diameter of the bulb.

The vortex electric field, generated by discharging pulse capacitors, shall be powerful enough to trigger avalanche ionization of the rarefied air inside the bulb. It is important to note here that artificially generated seed electrons might be required to facilitate the launch of the avalanche. Geometrical parameters of the configuration shall be adjusted in such a way that the radial component of the net force (i.e. centrifugal force plus Lorentz force), experienced by free electrons at the stage of current rise, is directed from the center of the bulb, and not to its center. This last condition is of paramount importance: it is this condition that makes creating a set of nested ruptures in the air possible, thereby forming relativistic double layer sheaths and restricting the motion of accelerated electrons in the confines of these sheaths.

5. Microwave Oven and Synchrotron Radiation of BL

Now we turn to another puzzling feature of BL, namely, the ability to melt or evaporate certain metal objects—gold jewelry, in particular—on its path. According to our model, BL is accompanied by a synchrotron radiation. What's the frequency range of this radiation? Synchrotron radiation is peaked on the frequency, which is associated with the cyclotron frequency, i.e. with $\nu_0 = c/\pi D$, as [5]

$$\nu_{max} = \frac{3\gamma^3\nu_0}{2}, \text{ where } \gamma \equiv \frac{E}{m_0 c^2}. \tag{10}$$

As we have noted earlier, by the time fireball gets to casual observer's line of sight, its ultrarelativistic electrons lose part of the energy to synchrotron radiation, retaining at best a few dozen MeV per electron. Let γ vary in the range 1–100, i.e., the energy of electrons in the double layer sheath is in the 0.5–50 MeV range. Then, for a typical fireball of 10 cm in diameter, $\nu_{max} = 1.43(10^9 - 10^{15})$ Hz. In other words, synchrotron radiation of BL is roughly in microwave to UV range. So, the assumption that BL is a source of X-rays, which is occasionally made in the literature, is most likely not correct.

Electromagnetic radiation in the microwave oven is of frequency 2.45 GHz and power around 1000 watts. These parameters correspond to that of synchrotron radiation from a fireball of small energy. This invites a curious question. What will happen if we put a metal object in a microwave oven? If BL emits electromagnetic radiation in the microwave range that is powerful enough to melt or evaporate parts of metal objects in an instant, then microwave oven should be able to do the same. With that thought in mind, I took three sewing needles 75 to 80 mm long each and attached them to a cardboard so that a triangle with small gaps at all three vertices is formed. I put all that on the rotating table of the microwave oven in my kitchen and turned it on for 10 s. Around the 7th second, a huge flame flared up and the cardboard caught fire. I turned off the oven as quickly as I could. The result of this experiment was that the sharp tip of one of the needles melted and turned into a ball in a fraction of a second. Thus, it seems that our understanding of the nature of BL can also account for the mysterious ability of fireballs to melt or evaporate parts of metal objects in a blink of an eye.

6. Controlled Nuclear Fusion and BL

Provided that we succeed in creating a fireball in a rarefied air inside a glass bulb of 10 cm in diameter, as described above, there is no reason why it cannot be done in a glass sphere of much larger diameter that is filled with heavy hydrogen gas $^2H_2$ at atmospheric pressure or even higher. Then, the positive layer of each double layer sheath would be comprised of deuterium nuclei. We have seen above that ultrarelativistic electrons are the main carriers of energy in BL. Deuterium nuclei, which form the inner positive layers of the sheaths in this case, will also be accelerated by the vortex field, but to considerably lesser degree compared to the electrons, so, in percentage terms, they do not contribute much to the net energy of BL. However, there is a point of larger importance to be made here.

The charge particles, which make up the sheaths, move so fast that the sheaths are perceived as virtual walls: most of the molecules of heavy hydrogen are reflected by the sliding blows of sheath particles, while some of the molecules will penetrate into the "wall" and become targets for direct collisions with the highly energetic deuterons. Figuratively speaking, the two layers of each sheath act as millstones, which grind all the "grains" that end up between them. Now the question is: do the deuterons have enough energy to fuse with the nuclei of atoms of heavy hydrogen molecules that leak into the "wall" and become collision targets? To estimate the energy of deuterons in the sheath, substitute doubled proton mass for the electron mass in formula (2), which we have derived earlier for the energy of electrons accelerated by the vortex field. Let $R = 0.35$ m, $B_a = 1.0$ T, then deuterons get accelerated to 0.73 MeV, while electrons—to 52 MeV.

These estimates are quite encouraging. Firstly, note that electrons stay well below the 100 MeV threshold, above which the losses to synchrotron radiation become unacceptably large. Secondly, the cross section for the two-channel fusion reaction, $^2H + ^2H$ –> $^3He + n$; $^2H + ^2H$ –> $^3H + p$, with the energy of striking deuterons at 0.7 MeV is about 0.08 barn, i.e. 80% of its maximum possible value of 0.1 barn. Therefore, if the density of the "target" (which, obviously, grows proportionally with the density of the hydrogen gas, in which the double layer sheaths are immersed) is high enough, an intense fusion reaction is to be expected. In other words, we might have a *nuclear* fusion reactor here, which operates on principles that are quite different from those of the *thermonuclear* fusion reactor.

Is it feasible to control the process of nuclear fusion, which takes place in this reactor, and can it be an efficient source of energy? Time will tell.

7. Discussion

Aside from exotic forms of matter (Bose-Einstein condensate, antimatter, etc.), contemporary physics deals with four states of matter only: solid, liquid, gas, and plasma. If we take on faith the characteristic features of BL and the pattern of its motion according to eyewitness reports, the problem with BL is that identifying its substance with any of these four states of matter leads inexorably to violation of one or the other law of physics. This explains why the range of hypothesis underlying speculative models of this phenomenon (the number of which is, probably, way over one hundred by now) is extremely wide, starting from the assumption of optical illusion and all the way to suggestions that fireball is kind of a black hole.

In this study we have shown that the most inscrutable features of BL—including long life, incredibly high density of energy content, low temperature, and the ability to melt or evaporate metal objects—can be accounted for without violating any laws of nature, provided that the substance of BL is not merely a homogeneous, fully ionized gas, but rather an intricate structure comprised of ordinary air plus a number of nested sheaths, each of which is a double electrical layer with voltage drop in the order of 100 kV. The findings indicate that BL is a real phenomenon of nature beyond reasonable doubt, and solving this riddle is likely to have implications, the importance of which can hardly be overestimated. In particular, the possibility of fundamentally new way of looking at the problem of controlled nuclear fusion is noted.

The working hypotheses for the mechanism of BL formation is electromagnetic induction in the wake of a powerful thunderbolt discharge. The future research shall be concentrated on attempts to produce BL in a lab. A fairly detailed experimental schema for carrying out this task in a modestly equipped laboratory has been outlined.

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Abbreviations

The following abbreviations are used in this manuscript:

BL ball lightning

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