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ARTICLE

Sound Into Light: On the Mechanism of the Phenomenon of Sonoluminescence

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It is argued that a liquid influenced by ultrasound is locally compressed, which leads to the formation of cavities inside the liquid. When in the resonance, the liquid boundary layer is stretched, i.e., its molecules diverge. At a critical increased distance between the molecules in the boundary level, the compressed liquid is suddenly rectified, which leads to the collapse of cavities. At the instant impact, some inertons are released from the inerton clouds of the molecules of the boundary layer. In the bubble's gas, electrons of the outer shell of molecules/atoms absorb these inertons and become excited for a time (as know from the experiments, approximately ~100 ps). After that the molecules/atoms return to the initial equilibrium state, emitting photons.

KEYWORDS: Ultrasound, Sonoluminescence, Inertons, Photons.

1. INTRODUCTION

Usually in a liquid ultrasound generates cavitation that at special conditions is able to induce the phenomenon known as sonoluminescence,[1–11] i.e., an emission of light from a single collapsed gas bubble trapped in an acoustic standing wave. A description of detailed experiments, which demonstrate unique properties of the system studied, can be read in review papers.[12,13] In those works the classical theory of bubble dynamics, the gas dynamics inside the bubble, the hydrodynamic and chemical stability of the bubble, the conditions that bring to stable single-bubble sonoluminescence and many other aspects of the phenomenon are elucidated. The Rayleigh-Plesset equation is usually used for the analysis of bubble wall dynamics;[13–15] besides, the Rayleigh-Plesset equation is supplemented by the bubble-wall Mach number,[16] which includes effects due to the compressibility of the liquid. However, efforts of many researches did not result in the understanding the phenomenon. In general the authors emphasize that the phenomenon of sonoluminescence pushes fluid mechanics beyond its limit.

In the mentioned works the researchers point out that in case of sonoluminescence the most optimal acoustic pressure is 1.2 to 1.5 times the atmospheric pressure p_0. Different liquids were tested, though the main results were obtained in experiments with water. Each water molecule is vibrating in ultrasound waves with an energy of about 1.5×10^{-30} J, whereas a photon originating from a single atom of the bubble region has an energy about 10^{-20} J (i.e., 6 eV) or higher. Hence it seems sonoluminescence involves a concentration of the energy density by a factor over 10^{10}. The time of collapse is about 15 μs; the rate of collapse is at least 4 times the sound velocity in the liquids studied (the interfacial Mach number approaches unity). The intra pressure in the collapsing cavity reaches a few thousand bars. The concentration of gas in water is close to the standard dissolved value, though the glow is brighter when a noble gas is added in the concentration of a few per cent only. The maximum radius of an expanded bubble is around 50 μm, which very quickly collapses to the value of around 0.5 μm. As the radius of the bubble is compressed to approach the minimal critical value R_c (the van der Waal's hard core), the concentrated input acoustic energy leads to the emission of a broadband flash of light. The maximum of the luminescence spectrum is in the ultraviolet area. The intensity of emitted light is much higher in the case of such liquids as sulphuric and phosphoric acids. The duration of emission is circa 50 to 100 picoseconds.

Although at the emission of light from bubbles the blackbody behavior is observed, a number of researchers[17,18] invoke plasma processes as the basis for explaining the light emitting mechanism. Nevertheless, they note that the state of matter that would admit photon–matter equilibrium under such conditions is a mystery.[18] The inability to reconcile the long photon mean free path with the smallness of the hot spot suggests new physics in the modeling of sonoluminescence.

The spectrum of light generated at higher acoustic frequencies is not well described by Planck's formula. Though the mechanism of the light emission remains uncertain, the main considerations are categorized under

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either thermal or electrical processes and are characteristic of formulas for thermal emission such as electron-neutral Bremsstrahlung.

However, to create plasma in the bubble gas, the value of the ionization potential has to be exceeded, which is around 15 eV.

Recent studies[19, 20] showed that dilute plasma models of sonoluminescence are not valid. The photon scattering length in the bubble is too large to explain the bubble's opacity. In work[19] this issue was resolved with a model that reduces the ionization potential. According to this model, sonoluminescence originates in a new phase of matter with high ionization. Bubbles in which sonoluminescence occurs can be 1000 times more opaque than what follows from the Saha equation of statistical mechanics in the ideal plasma limit. To address this discrepancy, the researchers[19] suggest that the effects of strong Coulomb interactions are an essential component of a first principles theory of sonoluminescence. The researchers[21] conclude that enough charge needed to create plasma in the bubble can be unbound by collective processes; by their estimate collective acoustic vibrations could be able to reduce the ionization potential by at least 75%.

The authors[22] hypothesized that the ionization energies of the molecules and atoms in the bubble decrease as the gas density increases at the bubble collapse and that the decrease of the ionization energy reaches about 60%–70% as the bubble flashes. Such hypothesis is an analogous of the formation of the conduction band in the interior medium of the bubble, which is definitely is not true.

There are also approaches that involve a vacuum to understand the phenomenon of sonoluminescence. Schwinger[23–25] proposed a physical mechanism for sonoluminescence in terms of photon creation from the zero-point energy field. He assumed that the surface of a bubble is able to act as the Casimir force plates and a sudden change of electromagnetic energy is emitted in the visible range as a sonoluminescent flash when the bubble collapses. Other researchers[26–32] reconsidered Schwinger's estimate of the Casimir energy involved in the emission of light by introducing new terms.

Musha[33] suggested to treat sonoluminesence as due to the Cherenkov radiation from tachyon pairs that are generated at a high temperature in the collapsing bubble as a result of the Casimir effect; the latter one is considered as the energy released from the zero point energy field, i.e., from a vacuum. However, in the recent paper by the author[34] it has been shown that the origin of the Casimir force is not related to the physical vacuum, also referred to as the zero-point energy field; the Casimir effect is associated with the discrete spectrum of vibrating atoms of the plates/surfaces studied and hence cannot be a source of the emission of light.

Mohanty[35] considered a hot gas in a bubble and calculated the first order correlation function of the electromagnetic field for two limiting cases of the excitation field: a blackbody spectrum and a discrete multi-frequency spectrum.

In paper[36] the authors explain sonoluminescence as a phase transition from ordinary fluorescence to a super-radiant phase. They consider a spin-boson model composed of a single bosonic mode and an ensemble of N identical two-level atoms. In an ultra-strong-coupling regime in the interior of the bubble with the electromagnetic field, the authors assume a cooperative interaction of the molecules of the gas (identical two-level molecules/atoms) and the field, which could generate sonoluminescence. Some researches tried to explain the phenomenon by considering a peculiar dynamic of hydrogen bonds (see e.g., short review[37]), which however, looks as too abstract.

So as we can see the researchers need free charges present in the interior of the collapsing bubble, because their presence could account for the observed emission of light. However, the major problem is lack of understanding whether free charges are available in a collapsing bubble or not. All the studies carried out so far both experimental and theoretical failed to establish the source of emission of light. Does the temperature inside the collapsing bubble really reach 6,000 to 20,000 K? It has never been measured directly. The researchers talk about a high temperature in the bubble and base this only on the viewable flashes of light, though during the experiment that lasts for a few minutes, the liquid under consideration does not change temperature. Therefore, the real origin of the emission of light in the phenomenon of sonoluminescence still remains unsettled.

Below we will see how the mechanism of sonoluminescence emerges from first submicroscopic principles. Initially we introduce the reader to a theory of the real physical space and demonstrate principles of the motion of a particle in the space, which unveils subtle details hidden from the formalism of conventional quantum mechanics. Then we will show how the methods of submicroscopic mechanics allow one to solve the issue of the emission of light from the collapsing gas bubble in a simple, elegant way.

2. KNOWLEDGE BASE

2.1. Space

In microscopic physics, or quantum physics, the notion of *space* is associated with an "arena of actions" in which all-physical processes and phenomena take place. And this arena of actions we feel subjectively as a "receptacle for subjects." The measurement of *physical space* has long been important. The International System of Units (SI) is today the most common system of units used in the measuring of space, and is almost universally used within physics.

However, let us critically look at the determination of *physical space* as an "arena of actions." In such a determination there exists, first, subjectivity and, second, objects themselves that play in processes that cannot be examined at all. For instance, size, shape and the inner dynamics of the electron remain unknown; the same for quarks in hadrons. Without a detailed knowledge of the notion of physical space it is impossible to answer such difficult questions, as: what is a photon?; what is the particle's de Broglie wavelength λ and Compton wavelength λ_{Com}?; how to understand the notion/phenomenon "wave-particle"?; what is spin?; what is the mechanism that forms Newton's gravitational potential Gm/r around an object with a mass m?; what does the notion 'mass' mean exactly?, etc.

In macroscopic physics "the arena of action as a reservoir for objects" also manifests itself, for example in a vehicle: when the vehicle suddenly hits the brakes, people sitting in the vehicle will feel that something pushes them forward. This something is the force of inertia that so far has fallen out of the interest of researchers.

Nevertheless, this "arena of actions" can be completely formalized, such that those mystical forces (veiled under the force of inertia and the centrifugal force) will unravel explicitly, because fundamental physical notions and interactions will be derived from pure mathematical constructions.

The generalization of the concept of space was done[38–41] through set-theory, topology and fractal geometry, which allowed us to look at the problem of the constitution of physical space from the most fundamental standpoint.

The fundamental metrics of our ordinary space, or space-time, is a convolution product in which the embedded part D4 looks as follows:

$$D4 = \int \left\{ \iiint_{\mathrm{dV}} [d\vec{x} \cdot d\vec{y} \cdot d\vec{z}] * d\Psi(w) \right\} \tag{1}$$

where dV is the element of space-time, $d\Psi(w)$ is the function that accounts for the expansion of 3-D coordinates of space-time to the 4th dimension through the convolution $*$ with the volume of space.

Set theory, topology and fractal geometry allow one to consider the problem of the structure of space as follows. According to set theory only an empty set $\varnothing$ can represent nothing. We can consider an ordered set, $\{\{\varnothing, \{\varnothing\}\}, \{\varnothing, \{\varnothing, \{\varnothing\}\}\}$, and so on. By examining the set, one can count its members: $\{\varnothing\} = \text{zero}$, $\{\{\varnothing, \{\varnothing\}\} = 1$, $\{\varnothing, \{\varnothing, \{\varnothing\}\} = 2$, $\{\varnothing, \{\varnothing, \{\varnothing, \{\varnothing\}\}\}\} = 3, \ldots$ This is the empty set as long as it consists of empty members and parts. However, on the other hand, it has the same number of members as the set of natural integers, $N = 0, 1, 2, \ldots, n$. Although it is proper that reality is not reduced to enumeration, empty sets give rise to mathematical space, which in turn brings about physical space. So, something can emerge from emptiness.

The empty set is contained in itself, hence it is a non-well-founded set, or hyperset, or empty hyperset. Any parts of the empty hyperset are identical, either a large part $(\varnothing)$ or the singleton $\{\varnothing\}$; the union of empty sets is also the same: $\varnothing \cup (\varnothing) \cup \{\varnothing\} \cup \{\varnothing, \{\varnothing\}\} \ldots = \varnothing$. This is the major characteristic of a fractal structure, which means the self-similarity at all scales (in physical terms from the elementary sub-atomic level to cosmic sizes). One empty set $\varnothing$ can be subdivided into two others; two empty sets generate something $(\varnothing) \cup (\varnothing)$ that is larger than the initial element.

The fractal dimension of the empty hyperset has a "fuzzy" dimension.

The concept of measure usually involves such particular features as existence of mappings and the indexation of collections of subsets on natural integers. Classically, a measure is a comparison of the measured object with some unit taken as a standard. Any space can be subdivided in two major classes: objects and distances. In spaces of the R^{n} type, tessellation by topological balls is involved, which again requires a distance to be available for measurement of diameters of intervals. Intervals can be replaced by topological balls, and therefore evaluation of their diameter still needs an appropriate general definition of a distance.

In physics, a ruler is called a metric. As a rule, mathematical spaces including topological spaces have been treated as not endowed with a metric, however, Michel Bounias[38–41] showed that all topological spaces are metric. Providing the empty set $(\varnothing)$ with mathematical operations $\in$ and $\subset$, as combination rules, and also the ability of complementary (C) we obtain a magma (i.e., fusion) of empty sets: Magma is a union of elements $(\varnothing)$, which act as the initiator polygon, and complementary (C), which acts as the rule of construction; i.e., the magma is the generator of the final structure. This allows the formulation of a theorem: *The magma $\varnothing^{\varnothing} = \{\varnothing, C\}$ constructed with the empty hyperset and the axiom of availability is a fractal lattice.* Writing $(\varnothing^{\varnothing})$ denotes the magma, and reflects the set of all self-mappings of $\varnothing$. The space, constructed with the empty set cells of the magma $\varnothing^{\varnothing}$, is a Boolean lattice, and this lattice $S(\varnothing)$ is provided with a topology of discrete space. A lattice of tessellation balls has been called a *tessel-lattice*,[38, 39] and hence the magma of empty hyperset becomes a fractal tessel-lattice. Introduction of the lattice of empty sets ensures the existence of a physical-like space.

If morphisms are observed then this enables the interpretation as a motion-like phenomenon, when one compares the state of a section with the state of a mapped section. A space-time-like sequence of Poincaré sections is a non-linear convolution of morphisms. The physical space-time then becomes one of the mathematically optimal morphisms and time is an emergent parameter indexed on non-linear topological structures guaranteed by discrete sets. This means that the foundation of the concept of time is the existence of orderly relations in the sets of functions available in intersect sections.

Time is thus not a primary parameter and the physical universe has no beginning: time is just related to ordered existence, not to existence itself. The topological space does not require any fundamental difference between reversible and steady-state phenomena, nor between reversible and irreversible processes. Rather, relations simply apply to non-linearly distributed topologies and from rough to finest topologies.

So real physical space has the form of a mathematical lattice: the tessel-lattice is regularly ordered such that the packing has no gaps between empty topological balls. Such tessel-lattice accounts for the existence of relativistic space and the quantum void (vacuum), as:
(i) the conception of distance and the conception of time are defined and
(ii) such space includes a quantum void, because the mosaic space introduces a discrete topology with quantum scales and, moreover, it does not have "solid objects," i.e., real matter, in its foundation.

The tessel-lattice with these characteristics has properties of a degenerate physical space. The sequence of mappings from one structural state to the other of an elementary cell of the tessel-lattice generates an oscillation of the cell's volume along the arrow of physical time.

However, there is also an option of transformation of a cell under the influence of some iteration similarity that overcomes conservation of homeomorphism. A change of the dimension means an acquisition of properties of "solid" objects, i.e., the creation of matter.

The organization of matter at the microscopic (atomic) level has to be based on a sub microscopic spatial ordering. Hence the crystal lattice is also a reflection of the sub microscopic ordering of real physical space that can be associated with the tessel-lattice of tightly packed balls—elementary bricks of the primary substrate of the universe.

In the tessel-lattice balls are found in a degenerate state and their characteristics are such mathematical parameters as length, surface, volume and fractality. Evidently, the removal of degeneracy must result in local phase transitions in the tessel-lattice, which creates "solid" physical matter. So matter (mass, charge and canonical particle) is immediately generated by space and has to be described by the same characteristics as the balls from which matter is formed.

It is reasonable to link the size of a ball in the tessel-lattice with the Planck length $\ell_{\mathrm{P}} = \sqrt{\hbar G/c^3} \approx 1.16 \times 10^{-35}$ m.

2.2. Submicroscopic Mechanics

The behavior of a canonical particle obeys submicroscopic mechanics that is determined on the Planck scale in the real space and is wholly deterministic by its nature. At the same time, deterministic submicroscopic mechanics is in complete agreement with the results predicted by conventional probabilistic quantum mechanics, which is developed on the atomic scale in an abstract phase space (see, e.g., Ref. [42]).

A volumetric fractal deformation of a cell of the tessel-lattice can be associated with the physical notion of mass, $m = C V_{\text{deg.cell}}/V_{\text{deform. cell}}$, where C is a dimension constant and $V_{\text{deg. cell}}$ stands for the volume of an original degenerate cell and $V_{\text{deform. cell}}$ for the volume of the deformed cell. In physics a resistance to the motion is called inertia. That is why excitations of the tessel-lattice produced by a moving particulate cell were called *inertons* (Fig. 1). These excitations carry fragments of the particle mass.

If we consider kinetics of the motion of such complex object—a particle surrounded with a cloud of inertons,—we derive relationships[42] for a particle as suggested by Louis de Broglie in 1924

$$E = h\nu, \quad \lambda = h/(m\upsilon) \tag{2}$$

Since relationships (2) have been obtained for a particle with the mass m and the velocity υ moving in the tessel-lattice, the sense of parameters in (2) becomes very clear: E is the energy of the particle, $m\upsilon$ is its momentum, λ is the spatial period in which the particle emits inertons and then absorbs them back, ν is the frequency of colli-sions of the particle with its cloud of inertons. Because of the periodicity, the moving particle periodically emits and absorbs its inertons, it is characterized by an increase in its action ΔS; since this is a free motion through the degenerate tessel-lattice, the increment ΔS is related to the Planck constant h.

The cloud of inertons occupies the section λ along the particle's path and spreads to a distance of $\Lambda = \lambda c/\upsilon$ in transversal directions, where c is the velocity of light.

De Broglie's relationships (2) allow one to obtain the Schrödinger wave equation.[39] But the relationships (2) obtained in our case signify that the Schrödinger wave ψ-function gains a real physical sense: ψ represents the

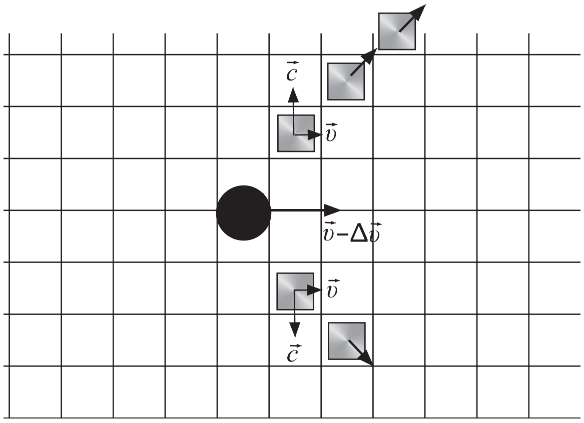

Fig. 1. Motion of the particle in the tessel-lattice. The particle slips between the tessel-lattice cells interacting with them. The collisions of the particle with oncoming cells results in the generation of excitations, i.e., the interaction knocks out inertons from the particle, which migrate by cells, hopping from cell to cell.

particle's field of inertia whose carriers are inertons and they carry mass and fractal properties of the particle.[40] Thus the particle's inerton cloud, which transfers the mass density through space, is mapping to the ψ-function of the formalism of conventional quantum mechanics. In such a way it became possible to actualize the de Broglie's program, which was presented in his last work:[45] "Interpretation of quantum mechanics by the double solution theory."

An inerton field completely obviates the action at-a-distance from quantum physics and introduces determinism at every stage of evolution of the system studied.[43, 44] The submicroscopic concept resolves a number of difficulties presented by quantum mechanics. Many phenomena in which inertons play a paramount role have been investigated—theoretically and experimentally—in series of our works: changes of physical parameters in aqueous solutions irradiated by an inerton field[46, 47] the formation of a cluster of electrons combined with inertons,[48] diffraction of light[49] and others.[34]

The electric charge emerges on the surface of a cell of the tessel-lattice as a quant of surface fractality:[50] needles directed inward topological balls characterize a negative charge, and needles directed outward imply a positive charge. The photon is an excitation that migrates in the tessel-lattice hopping from cell to cell,[51] which carries the surface polarization (negatively and positively directed needles, Fig. 2). Such construction easily leads to the Maxwell equations.[50]

For our future consideration Figures 1 and 2 are very important, as they represent real sub atomic patterns of physical processes that are too intricate to be described by the relatively rough formalism of conventional quantum mechanics. So an electron moving in the tessel-lattice is muffled with its cloud of photons-inertons. The inerton cloud accompanies the electron because the latter is a massive particle; hence massive inertons take about the electron. On the other hand the electron is a charged particle; hence its cloud of inertons should have an electrical polarization (such a cloud is the equivalent of the so-called virtual photons of quantum electrodynamics).

Basically in condensed matter physics it is a known fact that electrons may have an effective mass $m^* > m$. The origin of an additional mass usually has an electric origin. However, the mass may increase also due to the absorption of inertons. If the electron moves inside an inerton field (flow of inertons or the gravitation), it has to acquire an additional mass.[48] Then its cloud of inerton-photons becomes heavier, i.e., each inerton-photon also acquires an additional mass (Fig. 2(c)).

A similar situation occurs in the crystal lattice or any concentrated substance: entities that vibrate near their equilibrium positions periodically emit and reabsorb their inerton clouds. The amplitude of oscillations of an atom/molecule is nothing but the atom/molecule's de Broglie wavelength λ that obeys the relationships (2). If this is the case, then, as a result of some nonadiabatic processes the inerton cloud can be partially or completely knocked away from the atom/molecule. The entity is able to renovate its initial state in time by absorbing free inertons. But what happens with the released inerton cloud, i.e., a flow of mass? Theses inertons will be absorbed by the environment.

3. THE MECHANISM OF SONOLUMINESCENCE

Researchers note in the literature about a strong pressure in the collapsing bubble, which can reach a few thousand bar. However, this is a secondary effect, which appears as a result of the collapse. Initially the expansion of bubbles is due to ultrasonic energy that gradually compresses the liquid in such a way that impurities (especially gas atoms and molecules) are separated from the liquid, forming their own gas clusters.

Suppose we consider water. The surface layer of a bubble is composed of water molecules of course and can be conditionally called a boundary layer. In this boundary

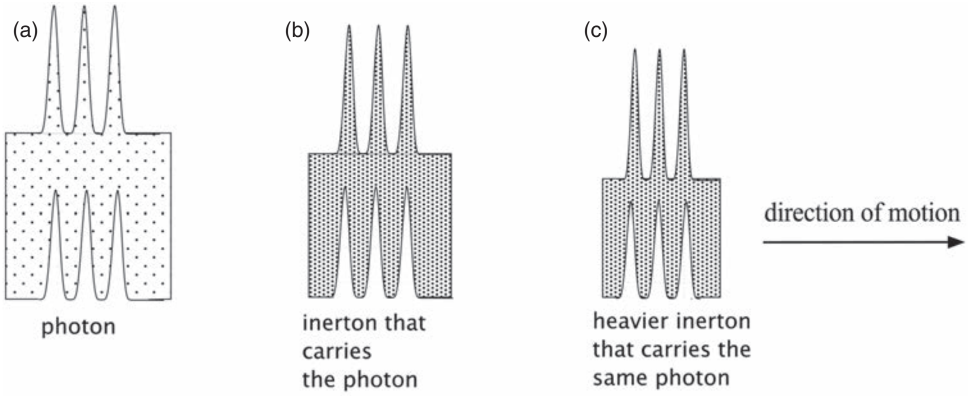

Fig. 2. Photon as the cell with the polarized surface. *a*–pure photon; *b*–photon formed on the inerton (the photon is characterized by a rest mass); *c*–photon formed on the heavier inerton (the photon is specified by a heavier rest mass). Note once again, by definition [34] the more cell is contracted, the greater mass of the corresponding physical excitation.

layer water molecules form a 2D network in which the mean distance d between molecules can be put as equal to the value typical for bulk water, 0.31 nm. But such a situation occurs only in the case of equilibrium between bubbles and water, which is possible at a low intensity of ultrasound, until the radius of a bubble is about 5 μm. With increasing exposure, the ultrasound will further squeeze the water, which will lead to the growth of the radius of the bubble. In its turn the mean distance d between water molecules in the boundary layer will also enlarge up to a critical value $d_{\rm c}$. At the value of $d_{\rm c}$ the boundary layer becomes unstable to the point of rupture: the squeezed water expands and quickly fills the cavity, which immediately results in the bubble collapsing.

Now let us consider what happens in the collapsing bubble. The total pressure inside the liquid under consideration, which leads to sonoluminescence, is the sum of the atmospheric pressure $p_0 = 101.325$ kPa at room temperature and the ultrasound pressure $p_{\rm u} = (1.2 \text{ to } 1.5)p_0$. Let $p_{\rm u} = 1.3p_0$, then the total pressure in the water is $p = 2.3p_0$. A typical frequency of ultrasound is 20 to 30 kHz, which means that during the time of collapse (15 μs) the pressure in the bubble does practically not change. Hence the work produced by the expanded water, which results in the bubble collapsing, can be estimated as

$$W = V_1p_1 - V_2p_2 \tag{3}$$

here the volumes are $V_1 = 4\pi R_1^3/3$, $R_1 = 50\times 10^{-6}$ m, and $V_2 = 4\pi R_2^3/3$, $R_2 = 0.5\times 10^{-6}$ m; the pressures are $p_1 = p + \sigma/R_1$ and $p_2 = p + \sigma/R_2$ where σ is the coefficient of surface tension of water; in the case of the water-air interface $\sigma \cong 73\times 10^{-3}$ N $\cdot$ m^{-1} at room temperature. Calculating the work (3), we obtain

$$W \cong \frac{4\pi}{3}R_1^3 p = \frac{4\pi}{3}R_1^3 \times 2.3p_0 \approx 1.22\times 10^{-7}\ \text{J} \tag{4}$$

Let us now calculate the number of water molecules in the boundary layer that separates the bulk water from the bubble of gas. The boundary layer is shown in Figure 3. We assume that the number N of water molecules is preserved in the membrane after the collapse of the bubble.

The value of N can be evaluated by using a simple expression

$$N = \frac{4\pi R_1^2}{d_c^2} \tag{5}$$

where $4\pi R_1^2$ is the area of the boundary layer at the moment of time before the bubble collapse; d_c may exceed the equilibrium value 0.31 nm two times, so let us put $d_{\rm c} = 0.63$ nm. This allows us to estimate the number of molecules in the boundary layer by using expression (5): $N = 1.55\times 10^{11}$.

The boundary layer, which is rapidly moving to the center of the bubble, experiences an abrupt resistance at the radius $R_2 \approx 0.5$ μm. This is because the gas compressed by the collapsing boundary layer and the state of gas becomes close to liquid (the size R_2 of the bubble of gas is determined by the van der Waals forces of the hard core of its contents[6]).

So, the boundary layer coming from the big radius R_1 to the small radius R_2 undergoes a sudden shock. As a result, a portion of inertons is stripped from the inerton clouds of the N water molecules of the boundary layer. The water molecules loose some mobility for a short time until the environment restores it again; the relaxation time for these molecules may fall in the millisecond range. Inertons released from the water molecules are directed to the center of the bubble (Fig. 3(b)).

Each shocked water molecule releases a batch of inertons, which can be presented as a single inerton (for each water molecule) with energy

$$E_{\rm inert} = W/N \cong 9.7\times 10^{-19}\ \text{J} \tag{6}$$

So each of these N inertons transfers the energy (6). The total number of these inertons should be subdivided as follows

$$N = N_{\rm backward} + N_{\rm ahead} \tag{7}$$

where $N_{\rm backward}$ are inertons reabsorbed by water molecules in the boundary layer (Fig. 3(b)) and $N_{\rm ahead}$ are inertons that are projected towards gaseous atoms contained in the collapsing bubble. The mass μ of a single inerton escaping from the boundary layer can be evaluated by an expression $E_{\rm inert} = \mu c^2$, which gives $\mu \cong 1.08\times 10^{-35}$ kg.

In the equilibrium state the radius of the bubble is around 50 μm. Such a volume can contain 1.75×10^{13} molecules of water. The number of gaseous atoms that fill this bubble is about 4–5 orders of magnitude smaller, i.e., the bubble contains 10^8 to 10^9 gaseous atoms (a mix of air and a noble gas). Typically a flash of light emitted from the collapsed bubble contains around 10^6 photons (in the case of a not too powerful ultrasound). Hence we may put $N_{\rm ahead} = 10^6$. This quantity of inertons reaches 10^6 atoms of gas.

In the gas the electrons of the outer shell of an atom rotate surrounded by its inerton-photon cloud (Figs. 1 and 2(b)). This inerton-photon cloud absorbs an inerton coming from the boundary layer, which immediately increases the rest mass of the electron m with the value of μ. The act of inerton absorption destroys the known conditions of the initial equilibrium state of the electron in the atom:

$$\frac{e^2}{4\pi\varepsilon_0 r^2} = \frac{m\upsilon^2}{r} \tag{8}$$

$$m\upsilon r = n\hbar \tag{9}$$

which result in the Bohr radius

$$r = \frac{4\pi\varepsilon_0\hbar^2 n^2}{e^2 m} \tag{10}$$

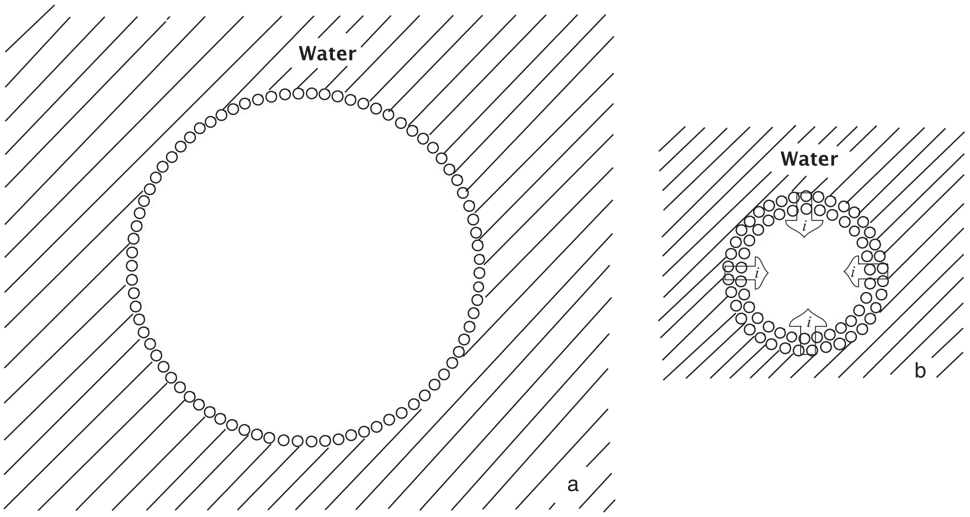

Fig. 3. One molecular layer of water molecules, the boundary layer, in the inflated bubble (a), which becomes the boundary layer of a few layers of water molecules after the collapse of the bubble (b).

That is why the electron must pass on to a lower intermediate orbit with a radius

$$r^* = \frac{4\pi\varepsilon_0\hbar^2 n^2}{e^2\cdot(m+\mu)} \qquad (11)$$

However the deeper orbit with the radius r^* is unstable. The inerton impacts the electron's inerton-photon cloud creating an excitation in it (Fig. 2(c)). In its turn the cloud has to respond to the impact, which should result in an oscillation process. Finally the inerton excitation gradually should spread along the whole inerton-photon cloud of the electron. The inerton excitation is completely dissolved in the cloud, which means its decay. As a result the compressed cloud emits a photon, which immediately restores the inerton-photon cloud and sets the electron in the stationary orbit with the radius r (10).

The problem under discussion is described by a differential equation of damped oscillations of the radius r, i.e., r oscillates between values of $(r \pm \delta r)$, Figure 4.

Namely, the equation reads

$$\delta\ddot{r} + 2\alpha\delta\dot{r} + (2\pi\nu)^2\delta r = 0 \qquad (12)$$

where 2α is the damping coefficient and $2\pi\nu$ is the cyclic frequency of the electron in the orbit of the radius r (10). It is reasonable to assume that the damping coefficient relates to the ratio of two masses multiplied by the rotation period ν^{-1} of the electron; namely, $2\alpha \equiv 2\nu^{-1}\mu/m$. Then the solution to Eq. (12) is

$$\delta r(t) \cong \delta r_0 \exp(-\nu^{-1} t\mu/m)\cos(2\pi\nu t) \qquad (13)$$

In the time $t = (\nu^{-1}\mu/m)^{-1}$ the oscillations practically decay, which means that this value determines the lifetime of the inerton excitation. In our problem, $m \approx 9\times 10^{-31}$ kg, $\mu \approx 10^{-35}$ kg and $\nu^{-1} \sim 10^{-15}$ s. Therefore the lifetime $t_{\text{life}} = (\nu^{-1}\mu/m)^{-1} \sim 10^{-10}$ s. After that a photon is emitted from the electron's inerton-photon cloud. The energy of the emitted photon is exactly the same as the energy of the absorbed inerton (6), $h\nu_{\text{ph}} = E_{\text{inert}} = 9.85\times 10^{-19}$ J, or 6.16 eV, which is between the middle and far ultraviolet; this result is in agreement with the experiments on sonoluminescence. The structure of outer electron shell in noble gases, in particular argon, permits the gases emit monochromatic light.

The estimated lifetime of $t_{\text{life}} = 100$ ps of the inerton excitation in the system {electron and its inerton-photon cloud} corresponds to the time delay between the bubble collapse and the emission of free photons measured in the experiments on sonoluminescence.

4. SUMMARY

The results obtained can be summarized as follows.

Ultrasound locally strongly compresses a liquid resulting in microscopic discontinuities in the compressed

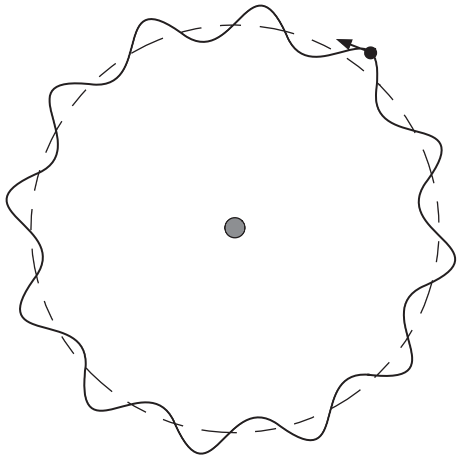

Fig. 4. Inerton excitation induces small oscillations of the radius r (10) of the stationary electron orbit.

region, which are known as vacuum caverns partly filled with a gas.

The collapse of a bubble is not a correct term, as in reality everything happens in reverse: the locally compressed liquid is expanded into the bubble, which is caused by the rupture of the stretched boundary layer that separates the compressed bulk liquid from the bubble. So the studies started by George Stokes and John William Strutt, 3rd Baron Rayleigh (Lord Rayleigh), and also the known Rayleigh-Plesset equation for the radius of a bubble in a liquid, cannot really be applied to the investigation of the phenomenon of cavitation dealing with a too rapid process. Because in classical works on hydrodynamics the liquid under discussion is considered as incompressible.

A flow of inertons is released at the sudden blow (i.e., the collapse) from molecules of the 'liquid–gas' boundary layer into the interior of the bubble.

In the gas inside the bubble the atom's/molecule's electron of the outer shell absorbs an inerton released from the boundary layer. After a short time the electron emits a photon and returns to its equilibrium orbit.

In conclusion we have to note that in the previous studies of the author[34] we dealt with inertons of the whole cloud of the object studied. In the present case of sonoluminescence, the situation is different: inertons are released only from a part of all the atoms of the system in question. In the next work, which deals with sonofusion and similar experiments, we will show that inertons, which are responsible for these unusual phenomena, are knocked out rather from a small quantify of atoms or even a single atom.

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