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Single Bubble SonoLuminescence of Particles model

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The Single Bubble SonoLuminescence is a phenomenon where the vapor bubble trapped in a liquid collapse by emitting of a light. It is very known that the temperature inside the bubble depends on the radius, during the collapse, the temperature can reach thousands of Kelvins and that the light would be emitted by radiation of the ionized gas inside the bubble. So, studies show that in certain cases neither an imploding shock nor a plasma has been observed and the temperature is not high enough to explain the spectrum observed. The Single Bubble SonoLuminescence remains a subject of study.

For this study we consider the bubble as a box where the free particles (particularly electrons) stemming from the molecules dissociation, are are trapped and confined within the bubble.

The confinement allows the particles to acquire some energy during the collapse which they lose in the form of light and also to be considered to bind to the bubble as an electron is bound to the nucleus in an atom. So, with regard to the bubble the energy of the particles can be considered to quantify, and with the quantum theory, by putting some hypotheses, their energy is determined well. The energy is physically acceptable that if the bubble is spherical.

This necessary condition of a spherical bubble of the model is observed experimentally in the collapse phase but not in the afterbounce phase of the bubble, explain why the bubble emits of light in the collapse but not in the phase of the afterbounces where she can be smaller, and constitute a validation of the Single Bubble SonoLuminescence of particles model.

For the application of the Single Bubble SonoLuminescence of particles model we consider a electron free particle of mass $m = 9.1094 \cdot 10^{-31} \text{ kg}$. We note that the interval of time between 6 eV and 2 eV energy (who can be considered as the duration when the bubble emits some light) is of the order of 40 picoseconds, the same order that the shortest pulses observed experimentally.

Key words: Sonoluminescence, Modeling, Particle, Quantum mechanics

1 Introduction

The sonoluminescence is a phenomenon where the vapor or gas bubbles trapped in a liquid collapse by emitting a short bursts of light (photons). There are two types of sonoluminescence : the sonoluminescence emitted by multiple bubbles (Multiple Bubble SonoLuminescence, MBSL) that enabled the first observations of the phenomenon by [1] and that emitted by a single bubble (Single Bubble SonoLuminescence, SBSL) highlighted by [2]. Bubbles can be produced during a cavitation, phenomenon by which vapour bubbles take place within a liquid submitted to a local pressure drop during an isothermal process ([3], [4], [5]), either by sound waves ([6], [7], [8]).

Experimental studies have shown the evidence of some phenomena following the sonoluminescence (mass and heat transfer between the bubble and the liquid, the chemical reactions, atoms ionization).

Thus, [9] by managing to create a single bubble of argon in a sulphuric acid solution subjected to the action of sound waves, obtained and measured the light flash spectrum.

So, the dissociation hypothesis that leads to stable Single Bubble SonoLuminescence (SBSL) in the water, based on considerations of chemical balance, emitted by [10] and experimentally verified by ([11], [12]), when the strong temperatures reached in the bubble at the time of its collapse leading for molecules dissociation of Nitrogen, Oxygen and the vapour present in the bubble produce multiple species (H, HNO₃, NH, NH₃, NO, OH, ...).

Besides, studies ([13], [10], [14], [15], [12], [16], [17]) show in a phase diagram (the bubble initial radius function of the acoustic pressure amplitudes) a sonoluminescence stability zone, where a bubble subjected to an acoustic pressure emits some light.

Also, in the occurrence of cavitation in hydraulic oil study, [18] highlighted a light emission by particles (Zinc, Nitrogen, Carbon, Hydrogen, Oxygen) contained in the oil, they explain that the observed phenomenon is different from the sonoluminescence. In 2006, [19] explain that this emission is due to an electric discharge, who itself is due to an accumulation of charge in zones of the cavitation. Even experimental studies ([20], [9], [21]) bring to light an emission from particles atoms (C₂, Ne, Ar, Kr, Xe, SO...) and ions (Ar⁺, Kr⁺, Xe⁺...) during Single Bubble SonoLuminescence

SBSL. This proves especially that particles (electron, atoms, ions) can be trapped and especially emit the light during the evolution of cavitation or the Single Bubble SonoLuminescence SBSL.

Subsequently, these studies have advanced the understanding of the phenomenon and to bring a scientific explanation. In this sense, certain authors suggest that the temperature inside the bubble depends on the radius. During the collapse, the temperature can reach thousands of Kelvins as demonstrated by ([22], [23], [9], [24], [8]), and that the light would be emitted by radiation of the ionized gas inside the bubble.

On the other hand, studies show that in certain cases neither an imploding shock nor a plasma has been observed ([25], [26], [6], [7]), but especially even if the temperature can be high it is not enough to explain the spectrum observed.

As we can see, a theoretical explanation of the sonoluminescence phenomenon remains a subject of study and constitutes a part of this work. In this present study we are particularly interested in a physical explanation of Single Bubble SonoLuminescence SBSL, where neither an imploding shock nor a plasma has been observed. To reach this objective, from one side we consider the dissociation hypothesis phenomenon and on the other hand the experimental report of the emission of particles light contained in the fluid during the onset of cavitation revealed by ([20], [19], [9], [21]).

In the literature, the evolution of a single bubble is modelled by the equation of Rayleigh-Plesset [27]. With the works of Van der Waals, it is known that the bubble is limited by an very fine interface, this last one can be a barrier for particles (atoms, ions, electrons) contained in the bubble.

The idea developed in this study is that during the collapse of the bubble, where according to the conditions she can reach nanometers or the same order than quantum dot size, the particles (atoms, ions, electrons) particularly electrons stemming from the molecules dissociation, are trapped and confined within the bubble, while certain species presenting very big water solubility are going to spread far from the bubble. With the uncertainty principle of Heisenberg ($\Delta x \Delta p_x \geq h$), this localization imposes on particles a strong excitement which allows them to acquire a strong energy and to be in an excited state. So, at the afterbounce of the bubble moment the particles of de-excitation by energy releasing in the form of photon, what explains the light emission. The particle is free in its

movement (not bound state), what allows him to emit on a wide range of wavelengths, where from the continuous spectre observed ([28], [29], [30]). As the particle remains confined in the bubble, then the particle can be considered to bind to the bubble as an electron is bound to the nucleus in an atom. So, with regard to the bubble the energy of the particle can be considered to quantify, and with the quantum theory, by putting some hypotheses, this energy can be determined.

The present paper is divided into two parts. Section one is dedicated to the models allowing to determine the particles energy and the section two focuses on the results and discussions.

2 Models

The radial movement of a single bubble without interaction is governed by Rayleigh-Plesset equation [27]. By putting the same hypotheses as [7], we have the following equation :

$$R \ddot{R} + \frac{3}{2} \dot{R}^2 = \frac{1}{\rho} (p_g - p_0 - p_a) - \frac{4\mu \dot{R}}{\rho R} - \frac{2\sigma}{\rho R} + \frac{R}{\rho c} \frac{d}{dt} (p_g - p_a), \quad (2.1)$$

With R the radius, \dot{R} the normal velocity to the interface, σ the surface tension, μ the dynamic viscosity, ρ the density of liquid, c the speed of sound, p_0 is the constant ambient pressure, p_g the gas pressure. For the modelization of this one we assume an isothermal equation of state, $p_g(R) = p_0 R_0^3 / R^3$ with R_0 initial radius. p_a the ultrasound driving, modelled as a spatially homogeneous, standing sound wave :

$$p_a(t) = -p_a \cos(\omega_a t), \quad (2.2)$$

Where p_a the acoustic pressure amplitudes and $\omega_a = 2\pi / T$, with $T = 1 / 26.5$ kHz. With the initial conditions, the equations (2.1) and (2.2) allow to determine the bubble movement. Concerning the particles contained in the bubble, we will be interested only by the energy which they can acquire.

To define the energy, we put the following hypotheses :

- We suppose that there is no interaction between the particles contained in the bubble, thus every particle is considered alone;

- The bubble remains spherical and its internal interface is supposed perfectly thoughtful and gives rise to shocks perfectly elastic ;
- We consider that particles move by making one comings and goings on an axis of length of the bubble diameter or describe a uniform circular movement plan of radius that of the bubble.

With these hypotheses the particles energy is given by that of the particle in an infinitely deep well or by that of a particle which describes a uniform circular movement in the plan. The equations of these energies are well known [31]. What is interesting it is the application in the sonoluminescence phenomenon.

2.1 Particle energy in an infinitely deep well

As the particle remains to border in the bubble. So, we can suppose a particle of mass m subjected to a potential energy $V(r)$ defined by :

$$V(r) = 0 \quad \text{pour} \quad -R < r < R, \quad (2.3)$$

$$V(r) = +\infty \quad \text{pour} \quad r < -R \quad \text{et} \quad r > R, \quad (2.4)$$

The particle movement is an one degree of freedom r and we suppose that the particle makes one to go with a constant velocity v , see figure 1.

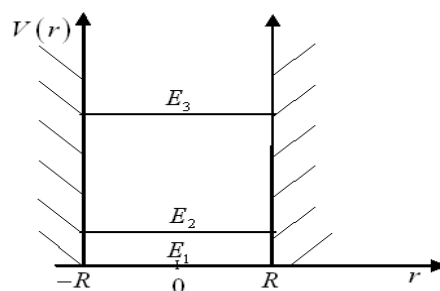


FIGURE 1. Comings and goings movement on axis r . The hatched parts indicate regions forbidden to particle.

The Plank's quantification condition gives :

$$\oint p dq = 4m|v|R = nh, \quad (2.5)$$

With p impulse of the particle, q coordinated generalized, n integer superior or equal to one, h Planck constant. So, the total energy equal to the kinetic energy is:

$$E_n = \frac{1}{2}mv^2 = \frac{n^2 h^2}{32mR^2}, \quad (2.6)$$

The equation (2.6) gives the particle quantified energy which moves on an axis of length equal to the diameter of bubble.

2.2 Particle energy in uniform circular movement

If the particle describes a uniform circular movement in a plan Oxy , see figure 1, with $q = R\varphi$ the position variable, $p = mR\dot{\varphi}$ the associated combined moment and φ the azimuth, the Plank's quantification condition gives :

$$\oint p dq = \oint mR^2 \dot{\varphi} d\varphi = 2\pi mR^2 \dot{\varphi} = nh, \quad (2.7)$$

There is a total energy :

$$E_n = \frac{1}{2}mR^2 \dot{\varphi}^2 = \frac{h^2}{8\pi^2 mR^2} n^2, \quad (2.8)$$

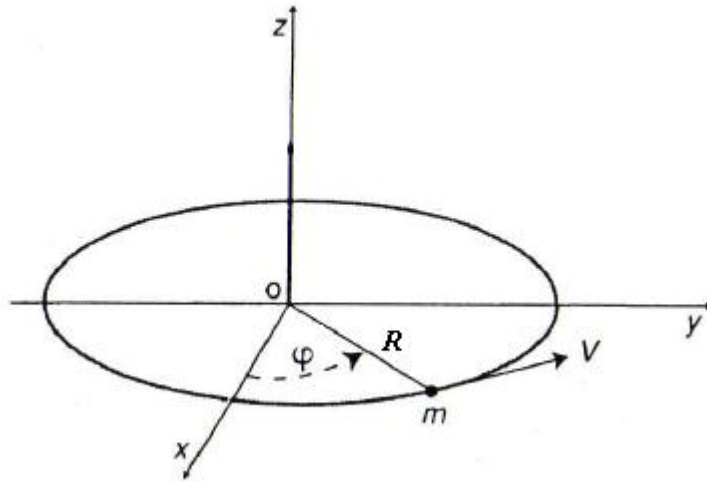


FIGURE 2. Uniform circular movement.

The equations (2.6) or (2.8) allow to determine the energy of a particle in an infinitely deep well or that of a particle who describes a uniform circular movement in a plan for every bubble radius, the energy is a function of $1/R^2$.

3 Results and Discussions

An isolated bubble in a liquid in equilibrium owes its survival to its internal pressure. On one side, the liquid pressure p_0 increased by the interfacial tension term $2\sigma/R_0$ tends to collapse the bubble, on the other side, the gas pressure contained in the bubble tends to dilate it. R_0 reflects this mechanical balance [32]. The main parameters of sound sonoluminescence bubble are the initial radius R_0 and the acoustic pressure p_a . So, in this study, we are going to study the influence of the initial radius R_0 , the pressure p_0 and the acoustic pressure amplitudes p_a .

Within the framework of this study we take place in the sonoluminescence stability zone given by [16], where the acoustic pressure amplitudes interval is of $1.3 \text{ atm} \leq p_a \leq 1.4 \text{ atm}$ and that of the initial radius is $2 \mu\text{m} \leq R_0 \leq 7 \mu\text{m}$.

Figure 3 presents for $p_a = 1.35 \text{ atm}$ and $R_0 = 4.5 \mu\text{m}$, the evolutions of the acoustic pressure, the radius and of the energy proportion $1/R^2$. For the bubble evolution, the different phases of the dynamics of bubble subjected to a sinusoidal pressure are described in the following studies ([33], [34], [7], [17]).

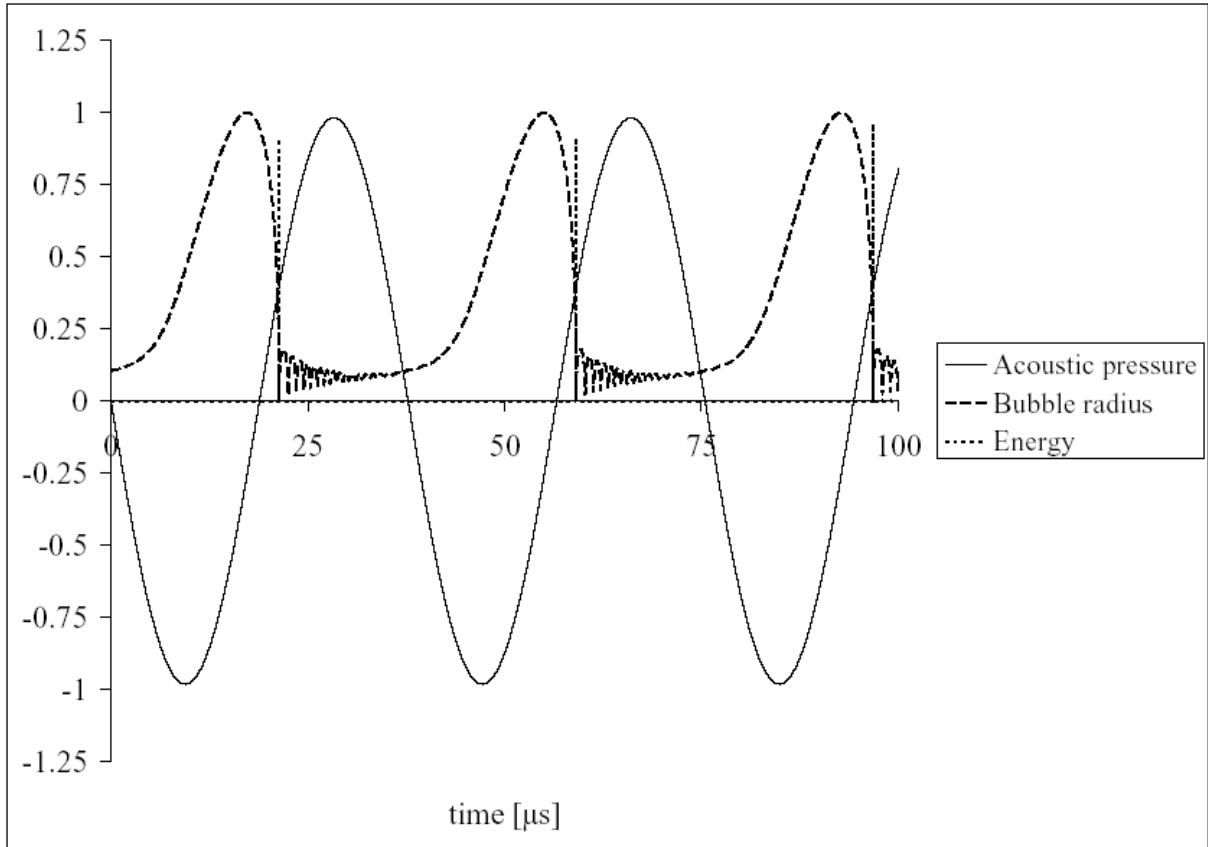


FIGURE 3 : The evolutions of the acoustic pressure, the radius and of the energy proportion $1/R^2$

Concerning the energy, E_n can take all the proportional values in $1/R^2$ that are physically acceptable, we notice an energy peak just in the first afterbounce of the bubble. It is exactly at this moment when the bubble emits some light. So, during the collapse of the bubble, the particle acquires a certain energy which it loses in the first afterbounce of the bubble by emitting of the light.

The energy E_n can take all the proportional values in $1/R^2$ which are physically acceptable. In both cases of movement, comings and goings and circular, the particle remains localized in the bubble as a particle in the box. As the undulatory model of the sound vibrations or the electromagnetic field inside the cavity which is a problem giving rise to standing waves, also, in the bubble case a physically acceptable situation has to lead also to standing waves.

To have standing waves, for the comings and goings movement case, it is necessary that $2R$ is equal to $n_w \lambda / 2$: $2R = n_w \lambda / 2$, with n_w integer number. So, for a particle about is the movement direction

to have a unique wavelength the bubble must be perfectly spherical. As for a vibrating rope of length $2R$ inside a bubble, the figure 4 represents an acceptable physical state (a) and unacceptable (b). In the circular movement case the circumference of the circle must be equal to integer of the wavelengths : $2\pi R = n_w \lambda$, figure 5 show the particle wave on a circle : an acceptable physical state (a) and unacceptable (b).

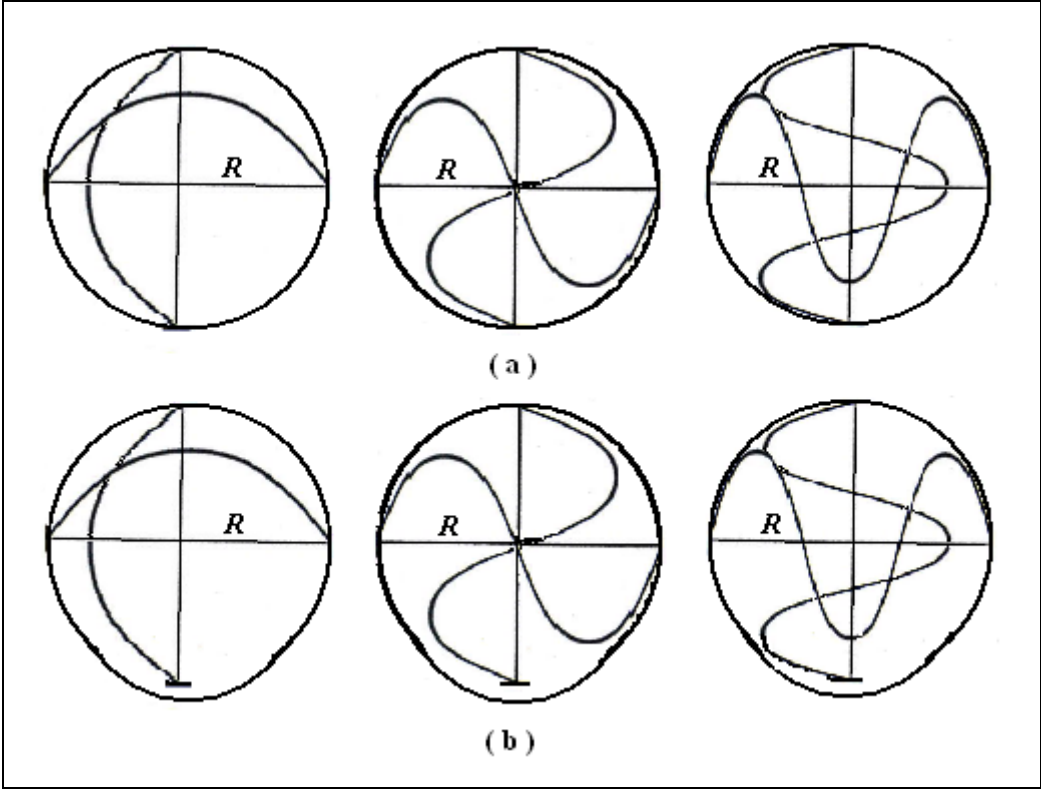


FIGURE 4: A vibrating rope wave of length $2R$ inside a bubble : an acceptable physical state (a) and unacceptable physical state (b)

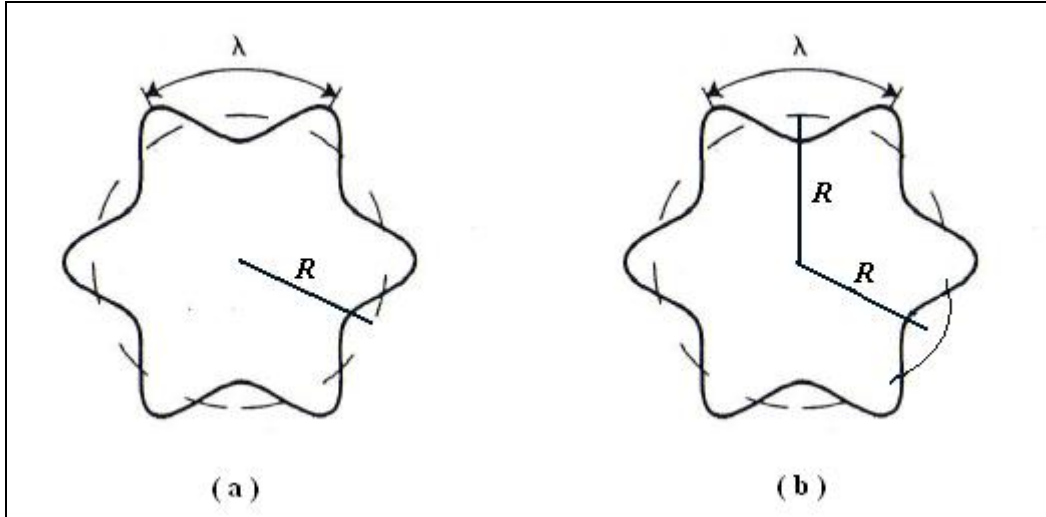


FIGURE 5 : The particle wave on a circle : an acceptable physical state (a) and unacceptable physical state (b)

So, to obtain a physically acceptable situation, that is for a particle have a unique wavelength all the time of the bubble evolution, the bubble has to remain stable but especially spherical. On one hand studies ([10], [26], [16], [35], [17]) confirm this hypothesis of outstandingly spherical stable bubble of Single Bubble SonoLuminescence during the collapse phase. On the other hand [16] has been directly observed the growth of instabilities during the afterbounce phase. As for a physically acceptable situation the bubble has to remain spherical this can explain why in the bubble afterbounces phase, where she can be smaller that in collapse, we do not observe a emission of light.

For the application of the Single Bubble SonoLuminescence of particles model we consider a electron free particle of mass $m = 9.1094 \cdot 10^{-31} \text{ kg}$. Concerning the energy level n , for a particle as a free electron which in passing of a low energy level : where it is bound to the nucleus, to the almost infinite level: where he is free, allows her to acquire a certain energy and to be in a excited state, we can consider n high.

Studies ([28], [36]) show that the emitted photon has an energy in the neighborhood of 6 eV . If we consider a bubble of $R_0 = 4.5 \mu\text{m}$ subjected to an acoustic pressure of $p'_a = 1.35 \text{ atm}$, we obtain a minimum radius of $R_{\min} \square 34 \text{ nm}$, this gives one n of the order of 272 and 427 respectively for a movement electron comings and goings and circular.

With this level of energy, on one hand with $R_0 = 4.5 \mu\text{m}$ we varied p_a' , one note that more p_a' is raised more the minimum radius is low and the energy E_n is raised : to see figure 6. On the other hand, with $p_a' = 1.35 \text{ atm}$ we varied R_0 , we note that more R_0 is low more the minimum radius is low and the energy E_n is raised : see figure 7.

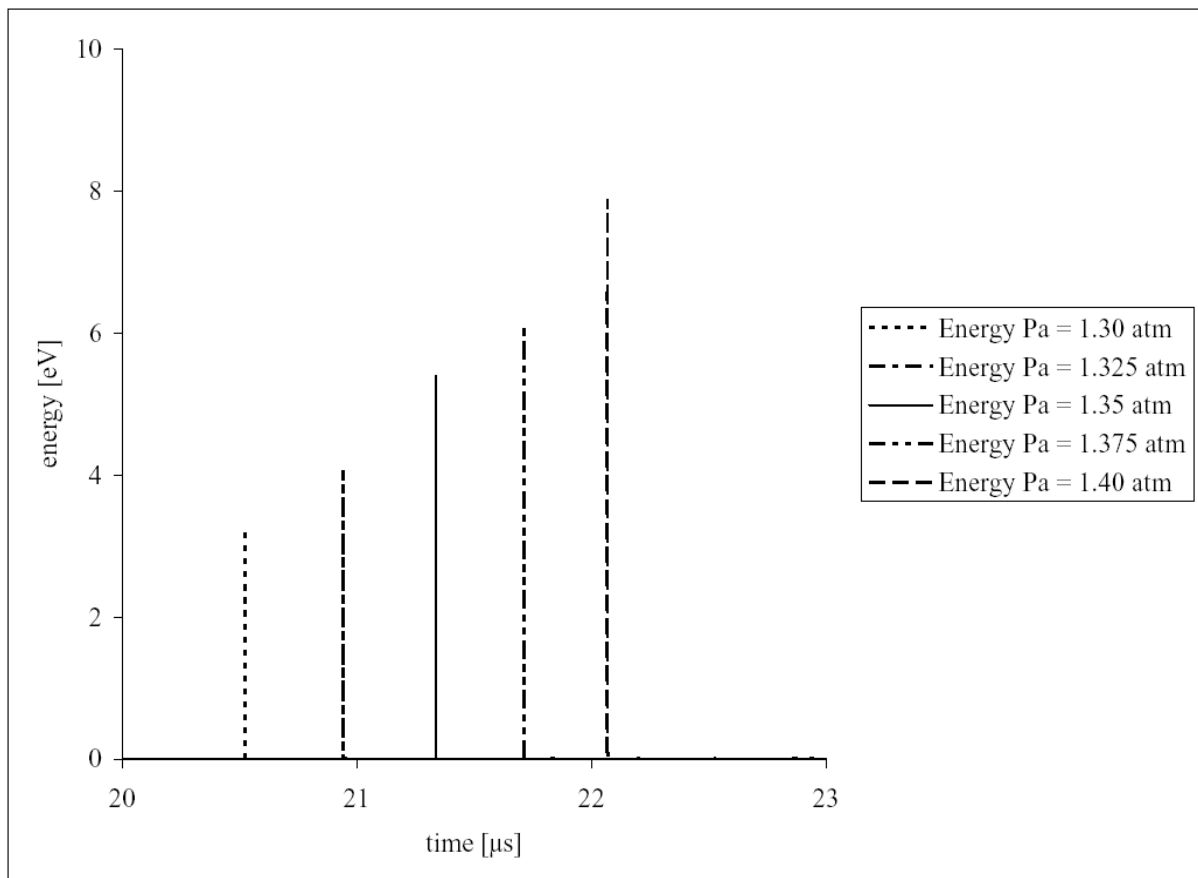


FIGURE 6 : Evolution of the energy in the zone of bubble collapse for $R_0 = 4.5 \mu\text{m}$ and different p_a' .

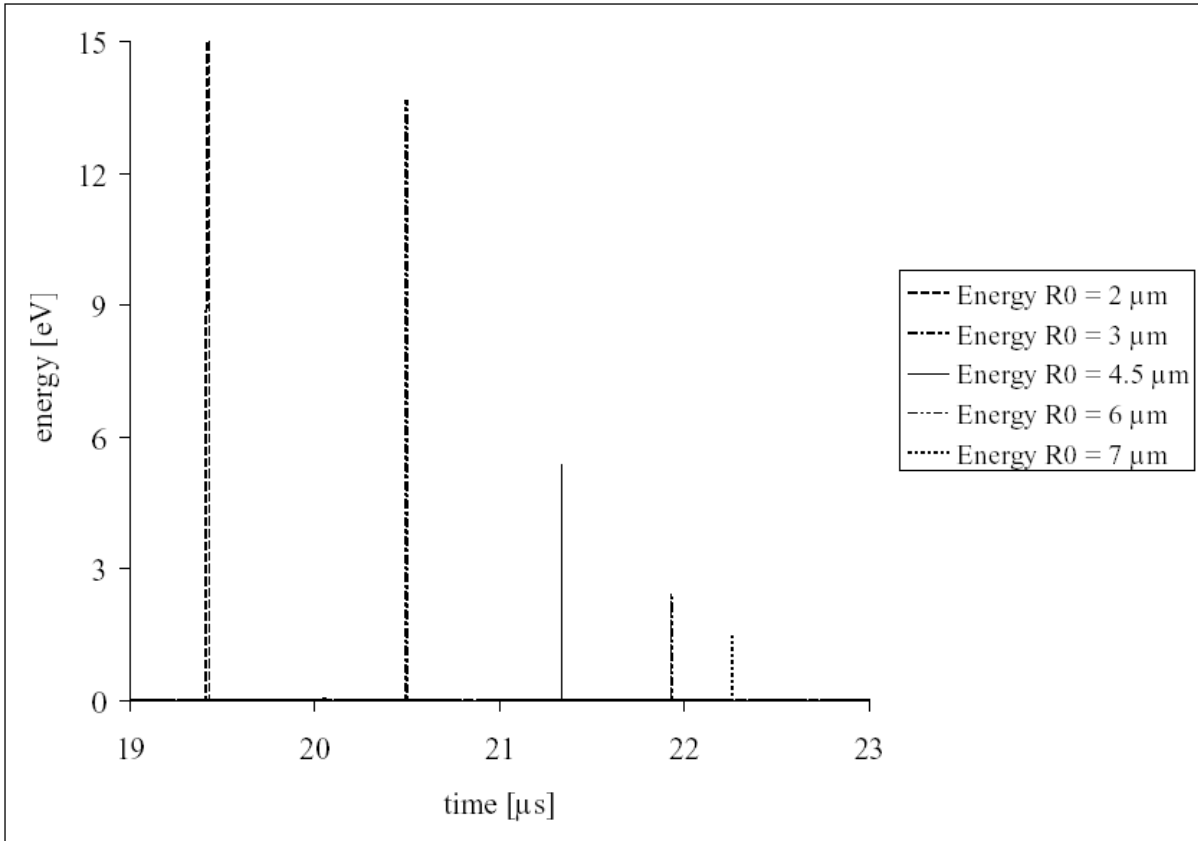


FIGURE 7 : Evolution of the energy in the zone of bubble collapse for $p_a' = 1.35 \text{ atm}$ and different R_0 .

The figure 8 is a zoom of the evolution of E_n , for $p_a' = 1.35 \text{ atm}$ and $R_0 = 4.5 \mu\text{m}$. It is very important to notice that the interval of time between 6 eV and 2 eV energy (who can be considered as the duration when the bubble emits some light) is of the order of 40 ps, the same order that the shortest pulses measure by [29] and [37] which is respectively of 60 ps ($\pm 6 \text{ ps}$) and 40 ps. Too [29] assert that we cannot exclude that there is a regime of stable SL where the pulse width is shorter than 50 ps. Before that, [38] by using faster detectors shows that the width of the sonoluminescence spike is actually less than 50 ps. Also [39] indicate that the SL duration is of the order of, or less than 12 ps.

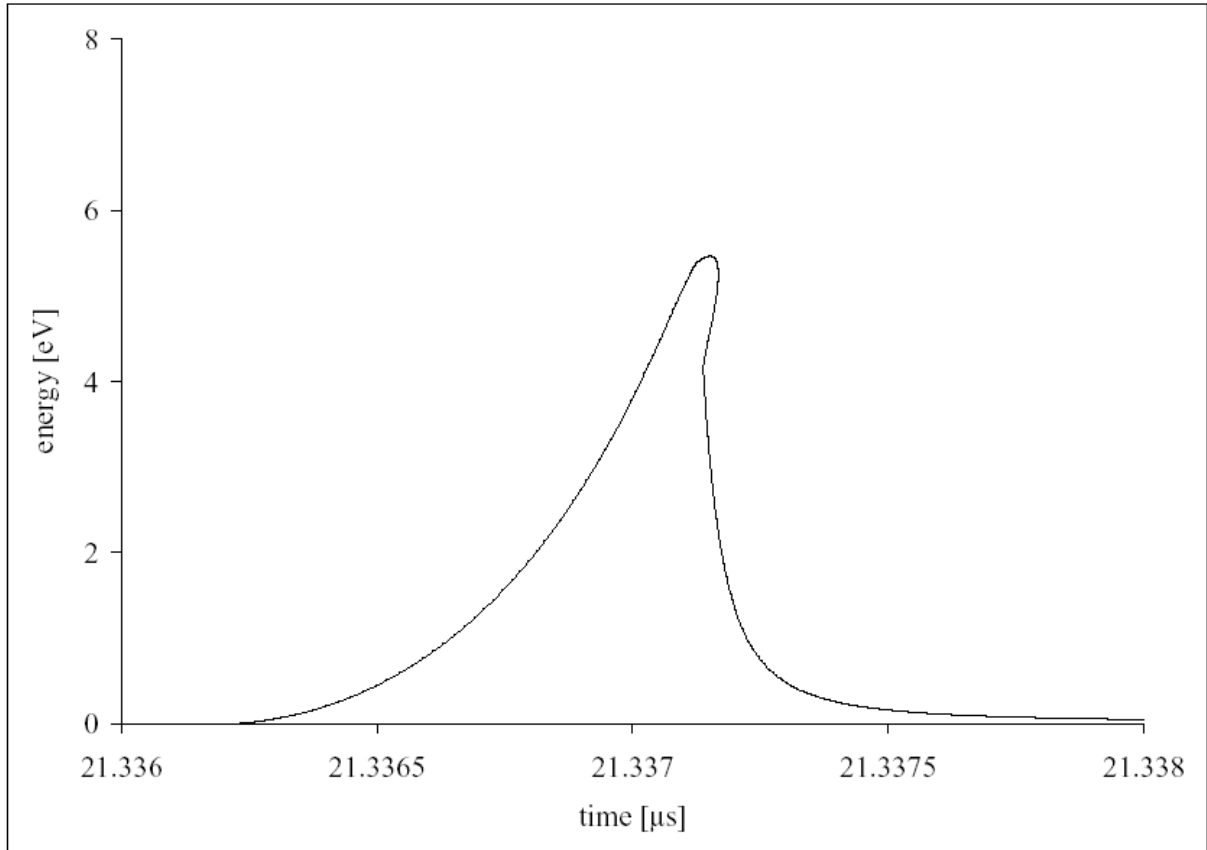


FIGURE 8 : Zoom evolution of the energy in the zone of bubble collapse for $p_a = 1.35 \text{ atm}$ and $R_0 = 4.5 \text{ } \mu\text{m}$.

4 Conclusion

This work dedicated to the theoretical study of Single Bubble SonoLuminescence SBSL, where neither an imploding shock nor a plasma has been observed. During the bubble evolution, some particles (particularly electrons), stemming from the molecules dissociation, are trapped and confined within the bubble. The confinement allows the particles on one hand to acquire of energy during the collapse, where the bubble becomes very small, which they lose in the form of light and on the other hand to be considered to bind to the bubble as an electron is bound to the nucleus in an atom. . So, with regard to the bubble the energy of the particles can be considered to quantify and with the quantum theory their energy is determined well. This energy is physically acceptable when the bubble is stable and spherical.

The sphericity of the bubble which, in view of this study is a necessary condition for Single Bubble SonoLuminescence of particles model, is observed experimentally in the collapse phase but

not in the afterbounces phase of the bubble. It explains why the bubble emits light to the collapse but not in the afterbounces phase where she can be smaller. This condition of spherical bubble can doubtless constitute a validation of the Single Bubble SonoLuminescence of particles model.

We note that in case the movement trajectory of the particle is an ellipse or a regular polygon inscribed in a circle which has for radius that of the bubble, where the trajectory (perimeter) which depends of the bubble radius can be equal to integer of the wavelengths, the bubble sphericity condition is necessary to obtain a unique wavelength (a physically acceptable situation) about is the particle movement direction.

Concerning the level of energy n , as bubbles emit the same frequencies of light, or n depends the Single Bubble SonoLuminescence SBSL parameters (p'_a and R_0) let be the bubble minimum radius R_{\min} is the same for all the bubbles.

We also note that the duration of the light emission estimated with the Single Bubble SonoLuminescence of particles model is the same order that the picosecond flashes observed experimentally.

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