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Sonoluminescence Unveiled ?

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Abstract:

The widening phenomenology of Single Bubble Sonoluminescence (SBSL), that is challenging generally accepted theory, is shown to be in good agreement with a new approach to condensed matter, based on the QED coherent interactions. The remarkable properties of SBSL are shown to emerge from the electromagnetic release of part of the latent heat of the water's vapour-liquid phase transition occurring at the bubble surface after it becomes supersonic.

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Sonoluminescence (SL) or, better, its recent, thoroughly studied version Single Bubble Sonoluminescence (SBSL) occupies a unique position in contemporary physics [1]. On one hand its study does not require neither the preparation of a complex, ill-characterized physical system nor the construction of a very sophisticated and very expensive apparatus: this has allowed many groups, within modest budgets, to carry out reproducible experiments, thus establishing the undisputable physical reality of the strange phenomenon whereby an acoustic field, through its pressure waves in water and other liquids, is able to cause a gas bubble to emit light up to maximum energy (about 6 eV) that can go, unattenuated, through water. Furthermore, the remarkably short (less than 50 ps) and synchronous (to within one part in 10^{11}) flashes emitted by the bubble during the final stages of its collapse, add in a dramatic way, to the oddity of the phenomenon. On the other hand, the consistent confirmations and extensions of the original observations [2] have posed a tremendous challenge to the theoretical physics of our days, that so far has found itself uncapable to give an explanation of the many oddities that SBSL has been constantly exhibiting over the last seven years. In spite of the many valiant theoretical efforts that have appeared in the literature, the generally accepted conclusion today appears that the phenomena of SL cannot be explained by known physics. Does this mean that the general physical laws of the Standard Model need a correction or an extension? We, like most of our colleagues, strongly believe that this is not, nor can be the case. But, then, how can we understand the incredible properties of the SL light flashes, both as to their photon energies and their time coherence? The photon energies correspond to a blackbody temperature in excess of 10^5 K, while the time coherence is in disagreement with both the blackbody [3],[4],[5] and the electron

[1]For a recent, very informative review see [1]

plasma mechanism [5].

In this Letter we present a theory of SL based on the general ideas of QED, and its coherent interactions in condensed matter. The first applications of this theory to a number of condensed matter systems have been expounded in a recent book [6], and are also available in the literature. Here, due to space limitations, we only mention that the application to water [7] [2] has shown that when a set of molecules of H_2O reach a density about one third the density of ordinary water, the system becomes unstable, and in a very short time (about 10^{-14} s) it condenses into liquid water. During the process of condensation, as we shall show and calculate below, the excess energy -about 0.26 eV per molecule- gets electromagnetically radiated in the surroundings with a typical, high energy spectrum.

Thus, the dynamical scenario that QED paints of SBSL is rather simple: when in the final phase of collapse the surface of the "imploding" bubble reaches a supersonic velocity with respect to the speed of sound in the water vapour, there begins a process of compression which, when the vapour's density reaches the value of 0.31 gcm^{-3}, leads to the formation of liquid water in a very short time with the release of excess energy (part of the latent heat) as a flash of light with a well defined energy spectrum, both in frequency and intensity. The rest of this Letter deals with the most relevant aspects of our theory.

According to the theory of QED coherence in matter [6],[7], when the density of the water molecules ρ is large enough ($\rho > \rho_c \simeq \frac{1}{3}\rho_{Water} = 10^{22}$ cm^{-3}) there exists a well defined excited state of the water molecule at the energy

[2] As the theory has only been worked out for water, in this Letter we shall only deal with SBSL in water, but we find, in principle, no reason why, *mutatis mutandis*, a strictly parallel chain of arguments may not be developed for any system whose phase at room temperature is the liquid.

ω_0=12.06 eV [3] that becomes the partner of the ground state in a coherent two-level oscillation in resonance with a coherent electromagnetic field whose spatial variation is determined by the wavelength $\lambda = \frac{2\pi}{\omega_0}$. This fact allows us to look at the system as an array of Coherence Domains (CD's), whose radii are $R_{CD} = \frac{\pi}{\omega_0} \simeq 500\ \mathring{A}$, inside which the average (complex) amplitude of the electromagnetic field $A(\tau)$ $(\tau = \omega_0 t)$ obeys the short times equation [6]:

$$\frac{i}{2}\ddot{A} \ + \ \ddot{A} \ + \ i\mu\dot{A} + g^2 A \ = \ 0, \tag{1}$$

which when μ <-0.5 ($g^2 \ll$1, as it happens for H_2O [7]) develops a run-away solution, i.e. an exponentially growing amplitude, signalling the transition toward a new state of the ensemble of molecules, the Coherent Ground State (CGS). Since the coefficient μ is proportional to $(N/V)^{1/2}$, it turns out that it is just at the critical density $\rho_c \simeq \rho_{water}$ [7], that μ=-0.5, and the phase transition from the vapour to the liquid occurs. During the transition, the ensemble of molecules gains the energy $\delta E \simeq$0.26 eV per molecule and the time-scale for the transition is very short, of the order of $\frac{10^2}{\omega_0} \simeq 10^{-14}$ sec. In a more complete and detailed work [8] we show that the stationary state for both the matter and the electromagnetic field is reached after a number of "Rabi-oscillations" at the frequency $\omega_R \simeq 1.1\omega_0$, with a characteristic damping time $t_{damping} = \frac{1}{\Gamma}$, where $\Gamma \simeq 1.5\ \omega_0$.

In order to have an idea of how the water vapour inside the bubble may reach the critical density ρ_c, and give rise to the "implosive" condensation into liquid water predicted by QED coherence, we must look at the dynamical evolution of the gas bubble during the compression half-cycle of the sound wave. Without entering into a detailed analysis of the rather complicated hydrodynamics of the bubble, it is sufficient to note that at the time t_0, when the velocity of the bubble radius $R(t)$ $[R(t_0) = R_0]$ becomes supersonic with respect to the sound velocity

[3] Throughout this paper we employ natural units, where $\hbar = c = k_B = 1$

in the gas, the system of gas molecules begins to be driven off thermodynamical equilibrium, the density inhomogeneities being unable to be leveled off through the propagation of (damped) sound waves. With respect to the "water-front" of the liquid proceeding toward the center of the bubble with increasing velocity, the gas molecules can be pictured as being (in the average) "frozen", and swept *in* by the imploding gas-liquid interface. At the time $t > t_0$ (See Fig.1) one expects that close to such interface there form a number of layers spaced by $a \simeq 3.2$ $\mathring{A}$, the average distance between H_2O molecules in the liquid, while the transverse spacing $a_T(t)$ is given by:

$$a_T(t) = a_0 \frac{R(t)}{R_0}, \tag{2}$$

where $a_0 = a_T(t_0)$ is the inverse of the third root of the vapour density ρ_0 at the time when the bubble becomes supersonic. In most treatments of the bubble collapse, at the time $t = t_0$ the gas temperature T is close to the water boiling temperature (383 K at p=1.4 Atm), where the vapour density $\rho_0 = \left(\frac{1}{a_0}\right)^3 \simeq 3 \cdot 10^{19}$ cm^{-3}, and the number of H_2O molecules in the bubble volume is given by

$$N_{H_2O} = \frac{4\pi}{3} R_0^3 \left(\frac{1}{a_0}\right)^3 = 1.14 \cdot 10^{10} \quad (R_0 \simeq 4.5 \mu m). \tag{3}$$

According to our theory, the bubble will continue to collapse until, at time $t = t^*$, the vapour density $\rho(t^*) = \rho^*$ becomes

$$\rho^* = \frac{1}{a} \frac{1}{a_T(t^*)^2} \simeq \frac{1}{3} \left(\frac{1}{a}\right)^3, \tag{4}$$

and the transition from vapour to liquid occurs, thus liberating the SL flash. Note that at this time

$$a_T(t^*) = a_T^* \simeq \sqrt{3} a = a_0 \frac{R^*}{R_0}, \tag{5}$$

which setting $a_0 \simeq 3.2 \cdot 10^{-7}$ cm implies ($R_0 \simeq 4.5 \mu m$)

$$R^* \simeq 0.8 \mu m. \tag{6}$$

We can estimate the thickness of the condensing shell from the equation:

$$4\pi R^{*2} T \frac{1}{3} \left(\frac{1}{a}\right)^3 \simeq \frac{4\pi}{3}(R_0^3 - R^{*3}) \left(\frac{1}{a_0}\right)^3, \tag{7}$$

which stipulates the equality of the number of H_2O molecules contained in the spherical shell between R_0 and R^* at the initial time $t = t_0$, with the number of molecules in the thin shell of radius R^* when the critical density is reached. For $R_0 = 4.5\mu m$, $R^* \simeq 0.8\mu m$ [See eq.(7)] and

$$T = \frac{R_0^3}{R^{*2}} \left(\frac{a}{a_0}\right)^3 \left[1 - \frac{R^{*3}}{R_0^3}\right] \simeq 1.4 \cdot 10^{-5}\ cm, \tag{8}$$

a bit over the size λ of a coherence domain, and about 5.7 times smaller than the bubble radius R^*. A rather sensible result.

A detailed treatment of the electromagnetic release of the "latent heat" of the vapour-liquid transition [8], shows that the classical electromagnetic current, associated with the oscillating two-level molecular systems, radiates the following e.m. spectrum per unit volume:

$$\frac{1}{V}\frac{dE}{d\omega} = \frac{3\omega_0^3}{16\pi^3}|c_1|^2 |F(\omega)|^2 \frac{\omega^2}{(\omega - \omega_R)^2 + \frac{\Gamma^2}{4}}, \tag{9}$$

where $|F(\omega)| = \exp\left(-1.4\left(\frac{\omega}{\omega_0}\right)^2\right)$ is the form factor of the water CD's, and the width $\Gamma \simeq 18$ eV is determined through the requirement that the total energy output equals 0.26 eV per molecule. The constant $|c_1|^2$ has the value 1.8. The complete spectrum [Eq.(9)] is reported in Fig.2, and a comparison with a typical experimental spectrum is shown in Fig.3.

Due to the water opacity for $\omega >$6 eV, only a small fraction of the 0.26 eV per molecule, about 0.03 eV, gets detected; the rest, which extends up to the large energy values 15÷20 eV, is either absorbed in water or by the gas molecules, thus rendering the bubble a unique, high energy chemical reaction chamber, as recently

noted in Ref.[9]. This observation appears particularly significant, since it clearly shows the important role of noble gases, whose excitation (ionization) energies lie above (or close to) the cut-off energy of the emitted spectrum. This means that these gases will be largely unaffected by the SL e.m. flash and their dynamical evolution is sensitive only to the hydrodynamics of the process, hence very stable from cycle to cycle. The situation is completely different for diatomic molecules, such as the N_2's or O_2's af air; their transformation into highly interactive free radicals will lead to their disappearance from the bubble, as recently noted [9]. This fact may also explain why for purely diatomic gases SL is so unstable and shows very strange memory effects [1].

As for the recent, very interesting observations of the temporal widths of the SL flashes, they seem to be in fair agreement with our theory, which predicts that:

1. all frequencies are emitted simultaneously, there being no delay effect for the low frequencies with respect to high frequencies;

2. the temporal widths do not depend on the nature of the bubble gases;

3. the actual values of the widths depend on the deviations of the imploding interface from sphericity, causing its different parts to reach the critical density at different times. Please note that giving such fluctuations the size of a CD (a rather reasonable assumption), i.e. $\lambda \simeq 10^{-5}$ cm, and considering a radius velocity at $R = R^*$ about $1.5{\cdot}10^5$ cm/s, yields $\Delta t \simeq$60 ps, of the right size.

Finally, regarding the coherence of the SL flashes, our theory predicts good coherence properties, for the observed e.m. radiation originates from the classical

currents associated with the two-level oscillations of the large number of H_2O molecules of the different ($\simeq$150) CD's.

Leaving a more detailed analysis to a future publication [8], we would like to stress that in this Letter we have tried to present the main conceptual paths that bring the general theory of QED to bear upon the fascinating phenomena of SL. The good, not only qualitative, picture that our theory yields of the widening SL phenomenology shows, in our opinion, that we now possess a rather adequate and sufficiently precise description of the dynamics of water and of its formation from a disordered assembly of vapour molecules, when their density reaches the threshold ρ_c. The association of this event with a remarkable burst of e.m. radiation of rather high frequency, whose spectrum and intensity we correctly predict, bears witness, we believe, to the basic electrodynamical nature of the gas-liquid phase transition of H_2O, which is at variance with the generally accepted views about water and condensed matter in general.

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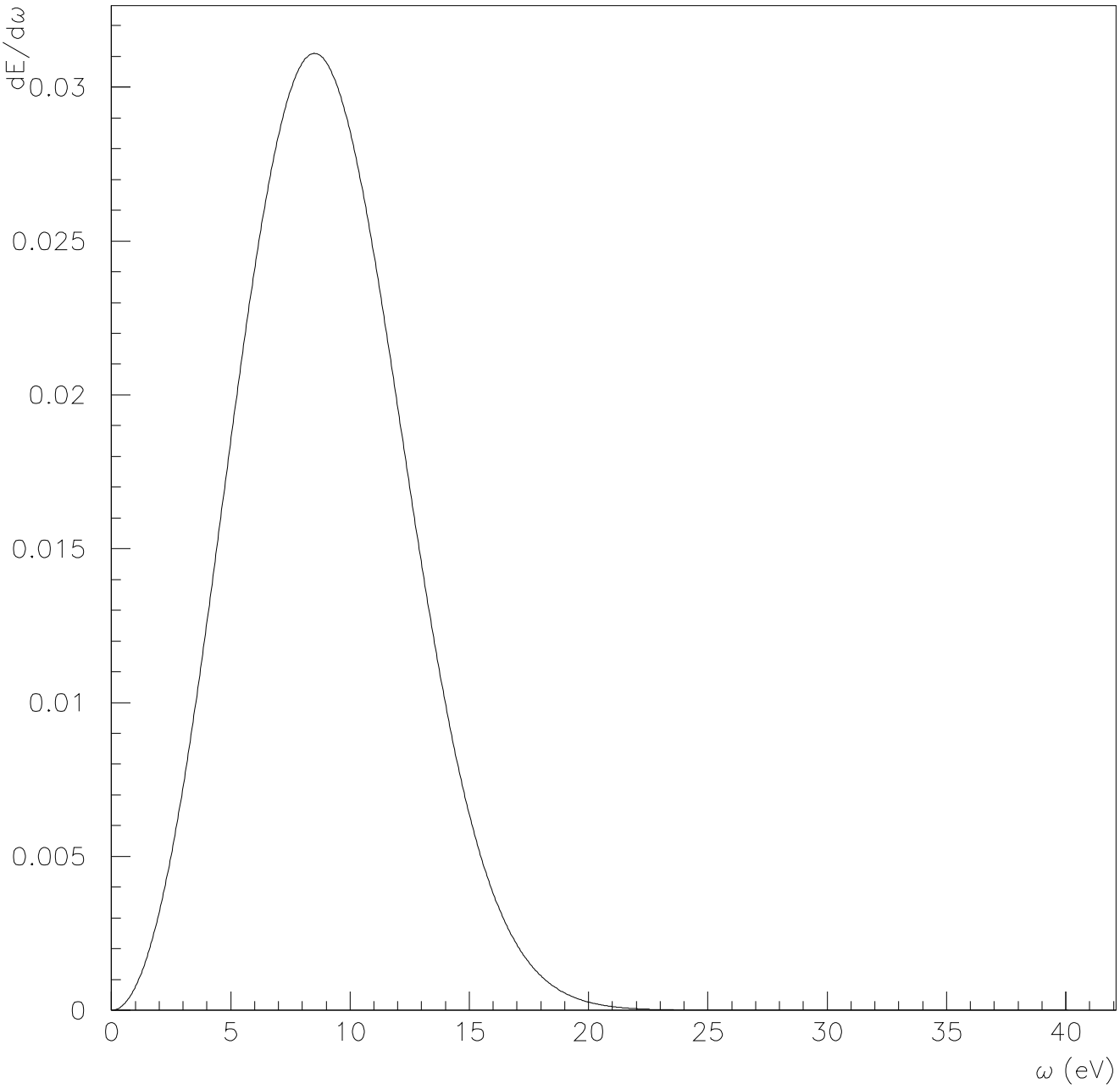
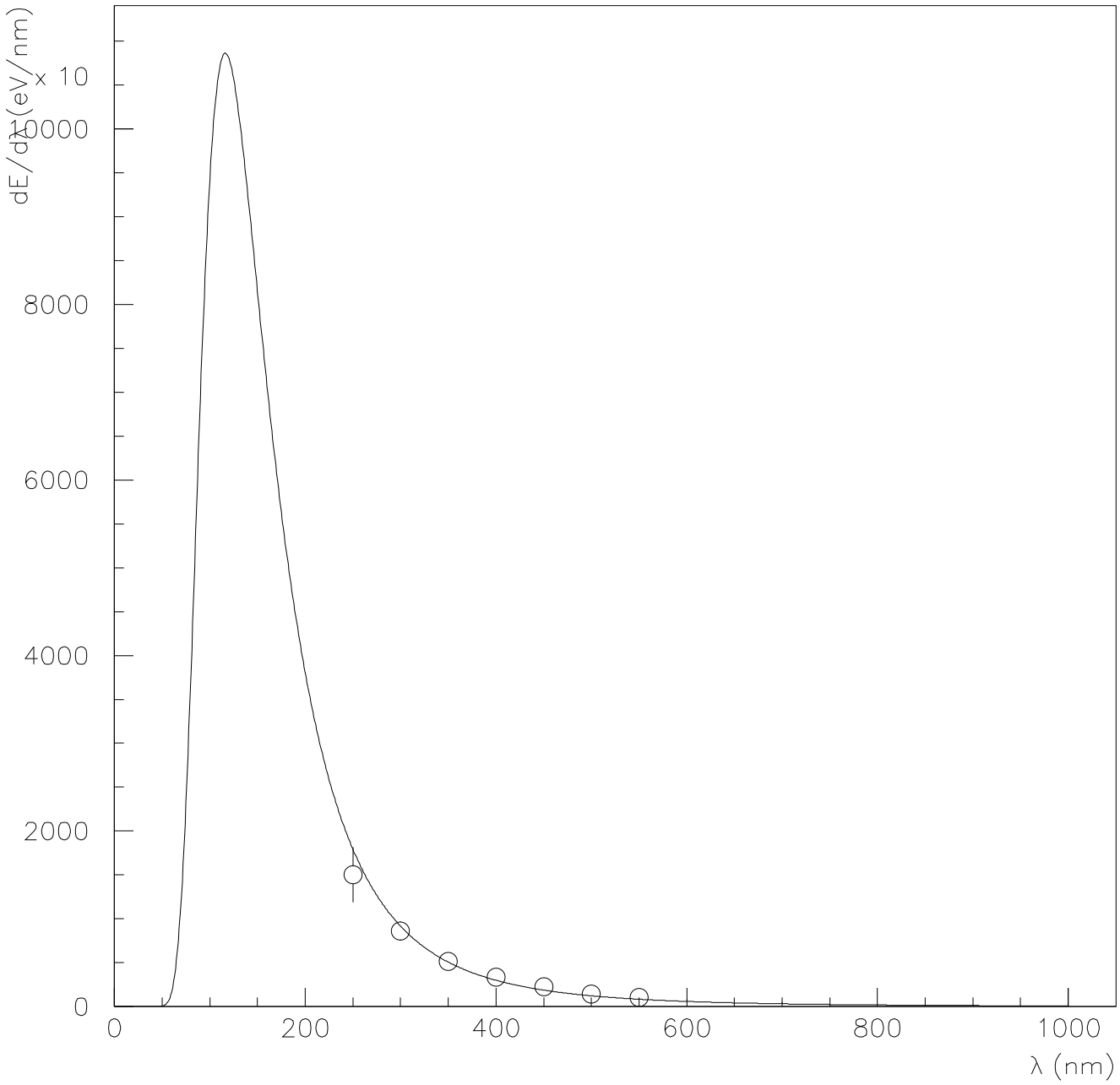
Figure Captions

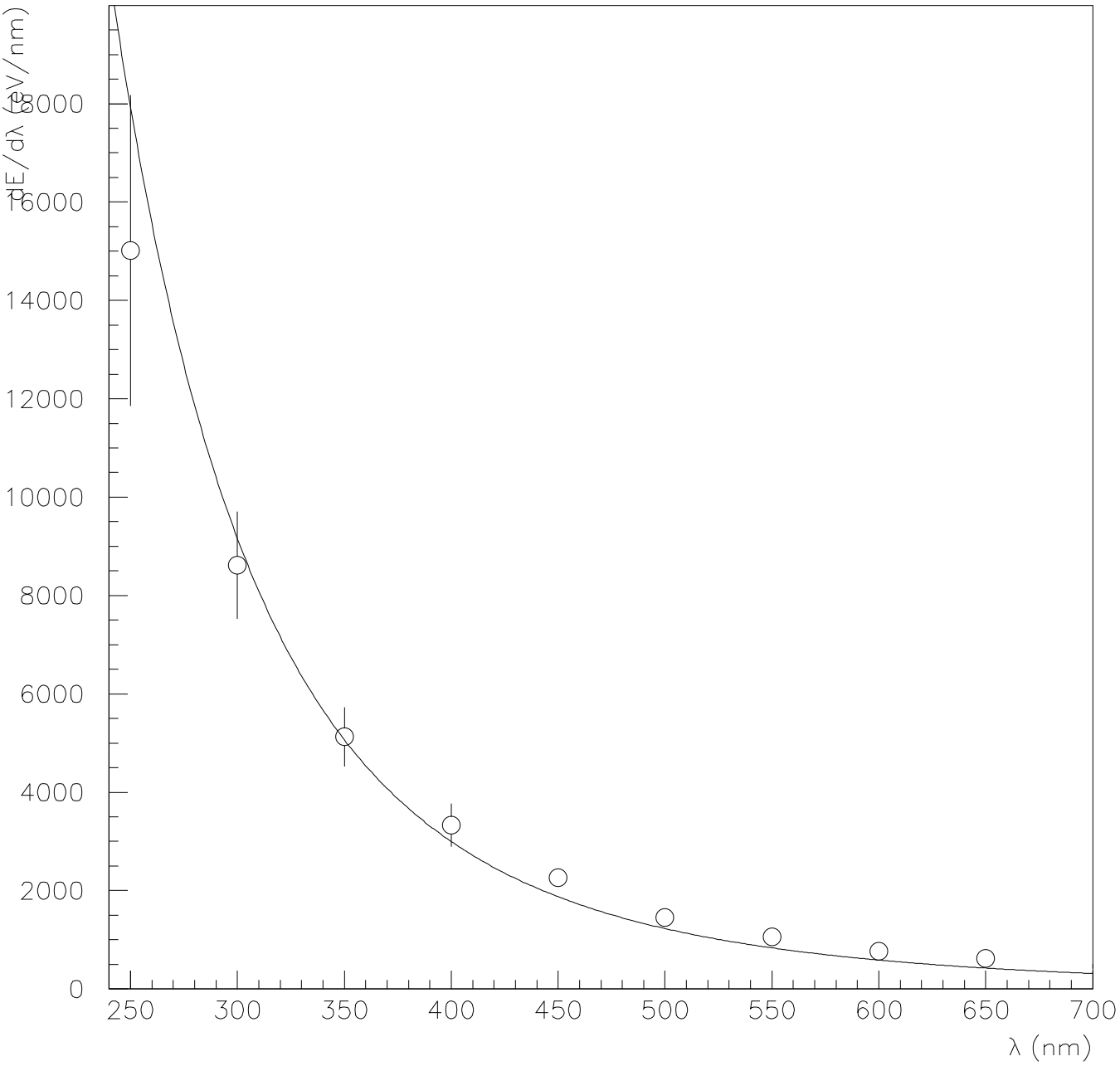
Figure 1: The relevant parameters of the collapsing bubble: R_0 = radius at which the compression becomes supersonic. R^* = radius at which the sonoluminescence burst is emitted.

Figure 2: The energy spectrum $dE/d\omega$ for one molecule; due to the water's opacity only the portion ω <5 eV of the spectrum is detected.

Figure 3: Comparison of the energy spectrum $dE/d\lambda$ irradiated in each sonoluminescence pulse with the experimental data.


dE/dω
0.03
0.025
0.02
0.015
0.01
0.005
0
0
5
10
15
20
25
30
35
40
ω (eV)


dE/dλ (eV/nm)
x 10
10000
8000
6000
4000
2000
0
0
200
400
600
800
1000
λ (nm)


dE/dλ (eV/nm)
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16000
14000
12000
10000
8000
6000
4000
2000
0
250
300
350
400
450
500
550
600
650
700
λ (nm)