

## The Standard Unit of Sonoluminescence

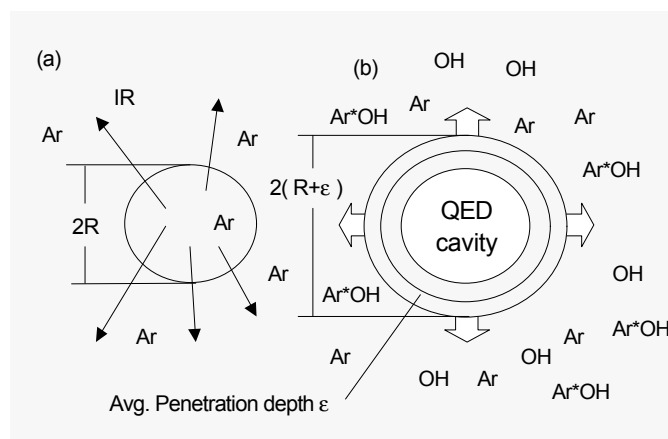
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**Abstract** Sonoluminescence (SL) is the visible light produced from the cavitation of bubbles in water. The Standard Unit of SL (SuSL) is the number of SL photons produced in a collapsing bubble in water containing dissolved air at ambient temperature, the SuSL found experimentally to be  $\sim 2 \times 10^5$ . Analysis is presented that shows SuSL is a consequence of the production of hydroxyl radicals from the electromagnetic (EM) radiation induced by cavity quantum electrodynamics (QED). The source of the EM radiation is the thermal  $kT$  energy of the water molecule that at ambient temperature is emitted at far infrared (IR) frequencies. The bubble at the instant of nucleation is treated as a QED cavity, the extent of the QED cavity including the penetration depth of the EM radiation in the bubble walls. Thus, the far IR radiation from the water molecules in the penetration depth is suppressed by cavity QED. To conserve EM energy within cavity QED constraints, the suppressed far IR energy loss is gained at the resonant frequency of the QED cavity; the process called cavity QED induced EM radiation. The Planck energy of the EM radiation within the penetration depth is shown sufficient to dissociate water into hydroxyl ions that react with argon in the air dissolved in the water to form  $\text{Ar}^*\text{OH}$  excimers, the number of which is consistent with the SuSL. Upon bubble collapse the  $\text{Ar}^*\text{OH}$  excimers decompose under the high pressures developed as the bubble walls collide, the decomposition producing SL light upper bound by a pulse width of about 400 ps.

### Analysis

SL is the visible light<sup>1</sup> observed in the cavitation of bubbles in water. SL in the cavitation of water may be explained with the theory of cavity QED induced EM radiation<sup>2</sup>. Consider a spherical water volume of radius  $R$  at the nanoscale in a state of hydrostatic compression as shown in Fig. 1(a). If the continuum is perturbed to a state of hydrostatic tension, an evacuated nanobubble of radius  $R$  is instantly formed as shown in Fig 1(b).



**Fig. 1** - Bubble nucleation in water

Surface tension may be neglected on the basis nanobubbles having diameters from 10 to 100 nm have been recently observed<sup>3</sup> on solid surfaces. Thus, either surface tension is non-existent at the nanoscale, or at the very least insignificant. If so, the nanobubbles form; otherwise nucleation is precluded. In water at atmospheric pressure, the surface tension 0.072 N/m requires a nucleation radius of 1.44  $\mu\text{m}$  containing a water particle.

<sup>1</sup> A.J. Walton, G.T. Reynolds, "Sonoluminescence," *Adv. Phys.*, 33, pp. 595-630, 1984.

<sup>2</sup> T. V. Prevenslik, "Cavity QED Induced Photoelectric Effect," *Proceedings ESA-IEJ Meeting*, Northwestern University, 25-28 June, pp. 230-240, 2002.

<sup>3</sup> J. W. G. Tyrrell and P. Attard, "Images of Nanobubbles on Hydrophobic Surfaces and their Interaction," *Phys. Rev. Lett.*, 87, 176104, 2001.

The purpose of this paper is to perform simple bounding SL analysis to estimate the SuSL based on cavity QED induced EM radiation. Nanoscale bubbles are assumed to nucleate in water absent surface tension.

### *QED Cavity and Suppressed IR Radiation*

In bubble nucleation having radius  $R < 30$  nm, the high EM resonant frequency of the QED cavity suppresses the low frequency IR radiation from the water molecules in the bubble wall, i.e., the bubble EM resonant wavelength  $4R$  is far shorter than that in far IR. But the extent of the QED cavity includes the bubble of radius  $R$  and the penetration depth  $\epsilon$  of the EM radiation in the bubble wall. The QED cavity resonant wavelength  $\lambda$ ,

$$\lambda = 4(R + \epsilon) \quad (1)$$

For a spherical bubble, the far IR energy  $U_{IR}$  suppressed in the penetration depth  $\epsilon$ ,

$$U_{IR} = \frac{4\pi}{3} \Psi \left[ (R + \epsilon)^3 - R^3 \right] \quad (2)$$

where,  $\Psi$  is the EM energy density,  $\Psi \sim N_{dof} \times \frac{1}{2} kT / \Delta^3$ ,  $\Delta$  is the cubical spacing between molecules at liquid density. For water,  $N_{dof} = 6$ . At density  $\rho = 1000$  kg/m,  $\Delta = 0.31$  nm. Thus,

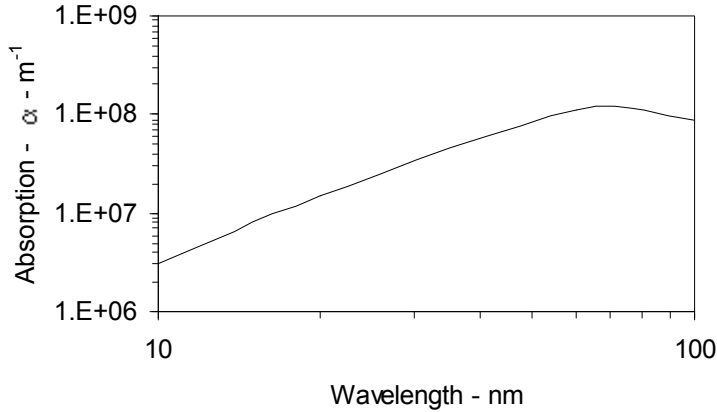
$$U_{IR} \sim 4\pi kT \left[ \frac{(R + \epsilon)^3 - R^3}{\Delta^3} \right] \quad (3)$$

### *Penetration Depth*

Beer's law gives the relation between the intensity  $I$  of the EM radiation at depth  $\epsilon$  to the intensity  $I_0$  at the bubble surface,

$$I/I_0 = \exp(-\alpha\epsilon) \quad (4)$$

where,  $\alpha$  is the absorption coefficient<sup>4</sup> of water shown in Fig.2.



**Fig. 2** Water Absorption Coefficient  $\alpha$  and Wavelength  $\lambda$

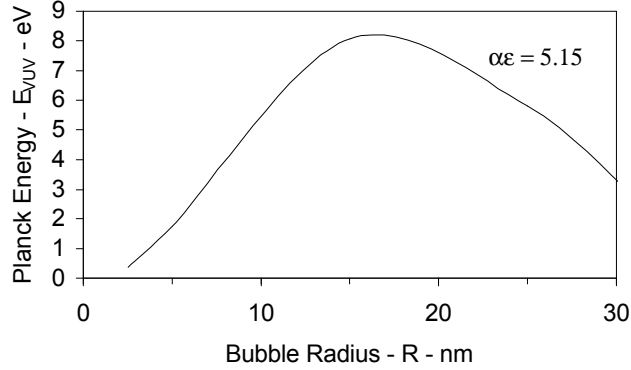
### *Conservation of EM Energy*

The suppressed far IR energy loss by the water molecules is conserved by the equivalent gain at the resonant frequency of the QED cavity. The conservation of EM energy,

<sup>4</sup> D. J. Segelstein, "The complex refractive index of water," MS Thesis, University of Missouri, Kansas City, 1981.

$$N_{\text{VUV}} E_{\text{VUV}} = U_{\text{IR}} \quad \text{and} \quad E_{\text{VUV}} = \frac{hc}{4(R + 0.5\epsilon)} \quad (5)$$

where,  $E_{\text{VUV}}$  is the average VUV energy over depth  $\epsilon$ ,  $N_{\text{VUV}}$  is the number of average VUV photons,  $h$  is Planck's constant and  $c$  is the speed of light. Fig. 3 shows the Planck energy  $E_{\text{VUV}}$  computed from the absorption data in Fig. 2. The parameter  $\alpha\epsilon = 5.15$  is selected to obtain maximum Planck energy  $E_{\text{VUV}} = 8.23$  eV that is of interest in the selection of the quantum yield of hydroxyl ions.



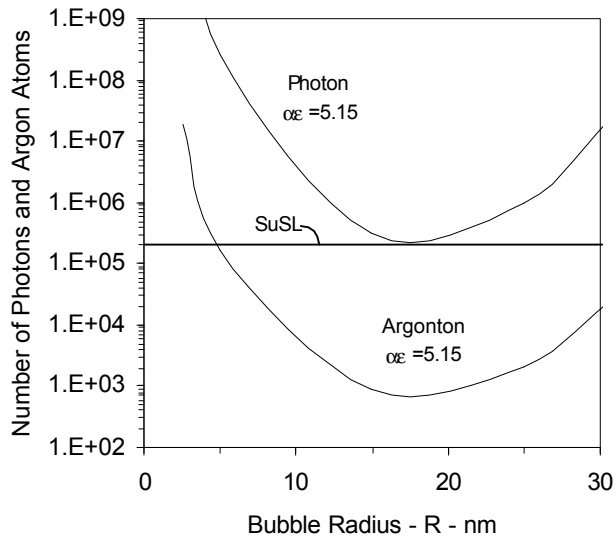
**Fig. 3** QED Cavity Radius  $R$  and Planck Energy  $E_{\text{VUV}}$

#### Number of QED Cavity Photons

The number  $N_{\text{VUV}}$  of photons produced in the QED cavity,

$$N_{\text{VUV}} = \frac{U_{\text{IR}}}{E_{\text{VUV}}} = \frac{16\pi kT(R + 0.5\epsilon)}{hc} \left[ \frac{(R + \epsilon)^3 - R^3}{\Delta^3} \right] \quad (6)$$

Fig. 4 gives  $N_{\text{VUV}}$  with the bubble radius  $R$ . For  $\alpha\epsilon = 5.15$ ,  $N_{\text{VUV}} \sim 2.3 \times 10^5$  VUV photons having Planck energy of 8.23 eV.



**Fig. 4** QED Cavity Radius  $R$  and Number of VUV Photons and Argon Atoms

### Number of Hydroxyl Ions

The dissociation yield  $Y$  of the water molecule gives the number  $N_{OH}$  of hydroxyl ions,

$$N_{OH} = N_{VUV} Y \quad (7)$$

At  $E_{VUV} = 8.23$  eV, the quantum<sup>5</sup> yield  $Y$  for photo dissociation of liquid water is,  $Y = 0.75$ . For  $N_{VUV} = 2.3 \times 10^5$ ,  $N_{OH} = 1.725 \times 10^5$ .

### Number of Argon Atoms

The number of argon atoms  $N_{Ar}$  in the penetration depth  $\epsilon$  depends on the mole fraction solubility  $\Phi$  of argon in water,

$$n_{Ar} = \Phi n_{H_2O} \quad (8)$$

or,

$$N_{Ar} = N_o n_{Ar} = N_o \Phi \frac{w_{H_2O}}{18} = \frac{2\pi}{27} \rho \Phi N_o \left[ (R + \epsilon)^3 - R^3 \right] \quad (9)$$

where,  $N_o$  is Avagadro's number and  $\Phi = 2.75 \times 10^{-5}$ . In Fig. 4 for  $\alpha\epsilon = 5.15$ ,  $N_{Ar} \sim 1000 < \text{SuSL}$ . But as the bubble expands, the OH ions are drawn into the bubble wall to react with any number of Ar atoms. Thus,  $N_{Ar}$  is unbounded.

### Number of Ar\*OH Excimers

The number of Ar\*OH excimers  $N_{Ar*OH}$  is limited only by the  $N_{OH}$  ions produced by the VUV photons,  $N_{Ar*OH} \sim N_{OH} = 1.725 \times 10^5 < \text{SuSL} = 2 \times 10^5$ .

### Duration of SL

The SL duration was determined<sup>6</sup> experimentally and found by single photon counting to be between 60 and 250 ps. By cavity QED induced EM radiation, the SL photons are produced by the decomposition of Ar\*OH excimers in the high pressures developed as the bubble walls collide with each other during collapse.

The analysis presented in this paper shows the OH ions are produced in the penetration depth and disperse in the bulk to react with Ar. Once formed, the Ar\*OH excimers should not significantly change their position relative to each other during cycling at ultrasonic frequencies. Typical penetration depth volumes of  $10^{-21} \text{ m}^3$  found in the analysis contain about 1000 argon atoms, and therefore to reach the SuSL, the OH ions need only migrate to a 200x larger volume, say to a cube  $S \sim 0.6 \mu\text{m}$  on a side. If so, the Ar\*OH excimer decomposition as the bubble walls collide should occur over a time  $t^* < S/V_s$ , where  $V_s$  is the sound velocity of 1480 m/s in water. Thus,  $t^* < 400$  ps and the simple analysis provides an upper bound to the measured SL pulse widths of 60 to 250 ps.

## Conclusion

The SuSL is given by the number of Ar\*OH excimers produced at bubble nucleation because the same number decompose to produce SL light<sup>7</sup> under the high pressure developed as the bubble walls collide at bubble collapse. The experimental<sup>8</sup> value of the  $\text{SuSL} = 2 \times 10^5$  is reasonably approximated by the number of OH ions produced by cavity QED induced EM radiation.

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<sup>5</sup> A. Mozumder, "Ionization and excitation yields in liquid water due to primary irradiation: Relationship of radiolysis with far UV-photolysis," *Phys Chem. Chem. Phys.*, 4, 1451-6, 2002.

<sup>6</sup> B. Gompf, R. Gunther, G. Nick, R. Pecha, and W. Eisenmenger, "Resolving sonoluminescence pulse widths with single photon counting," *Phys. Rev. Lett.*, 79, 105, 1997.

<sup>7</sup> T. LePoint, et al., "Observation of 'Ar-HO' van der Waals molecules in multibubble sonoluminescence," *Ultrasonics International* 2001, T.U. of Delft, 2-5 July 2001.

<sup>8</sup> R.T. Hiller, K. Weninger, S.J. Putterman, B.P. Barber, "Effect of Noble gas doping on single bubble sonoluminescence," *Science*, 266, 248-250, 1997.