

Single Bubble Sonoluminescence*

PHYS 128, Senior Lab

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*This lab was adapted from the TeachSpin material found at: <http://www.sonoluminescence.com>

I. INTRODUCTION

Single bubble sonoluminescence, hereafter abbreviated SBSL, was discovered in the late 1980s and has since received a great deal of attention. This remarkable process involves, at its core, trapping a gas bubble at a sonic anti-node location in a resonance mode of a cell. The exact geometry of the cell is not important, but it is necessary that there exist a spatial pressure gradient in order for the bubble to be positionally stabilized. In the presence of the alternating cycle of acoustic pressure the bubble expands and collapses. When the amplitude of the pressure becomes large enough, the collapse of the bubble enters a new regime in which the radius collapses to its hard core limit, heating up the gas contents inside and emitting a very brief but copious amount of light, which can be seen with the unaided eye.

A. Governing equations

Although the emission mechanism along with a number of other properties of SBSL are still not fully understood; the basic hydrodynamic equations governing the gross motion of the bubble have been around for quite a while and do accurately describe over 99.9% of the bubble's motion. Equation 1, The Rayleigh Plessett, has been used extensively to describe the motion of the bubble in its many regimes.

$$\begin{aligned}
 -R\ddot{R} \left(1 - \frac{2\dot{R}}{c}\right) - \frac{3}{2} \left(\frac{d^2R}{dt^2}\right)^2 \left(1 - \frac{4\dot{R}}{3c}\right) + \frac{P(R,t)}{\rho} + \\
 \frac{R}{c} \frac{dP(R,t)}{dt} - \frac{P_a(0,t)}{\rho} - \frac{R}{\rho c} \frac{dP_a(0,t)}{dt} - \frac{P_0}{\rho} = 0
 \end{aligned} \tag{1}$$

with the boundary at the fluid gas interface given by:

$$P(R,t) + \frac{4\eta\dot{R}}{R} + \frac{2\sigma}{R} = P_g(R,t) \tag{2}$$

and the use of Van der Walls hard core, a , in the ideal gas law to give the gas pressure P_g :

$$P_g(R) = \frac{P_0 R_0^{3\gamma}}{(R^3 - a^3)^\gamma} \tag{3}$$

where R is the bubble radius, c is the speed of sound in the fluid, ρ is the density, γ is the viscosity, P_a is the acoustic pressure, and P_0 is the ambient pressure. Among the first properties that were observed was the very brief nature of light emission. Initial measurements using high speed photomultiplier tubes placed an upper limit of 50ps

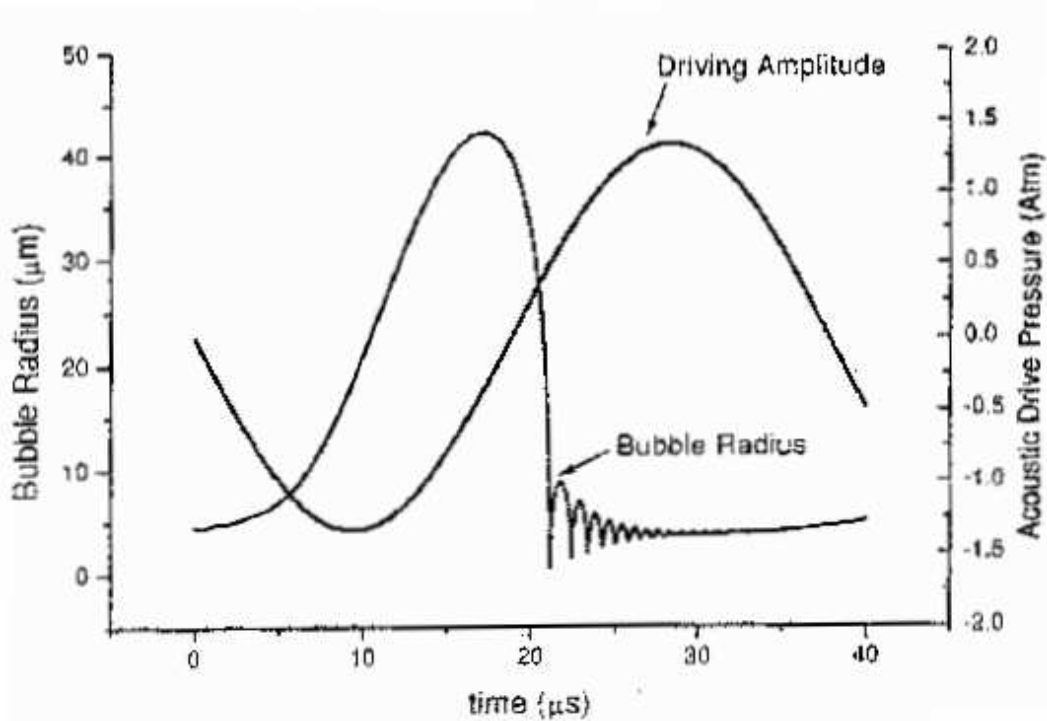


Figure 1: A graph of the bubble radius and driving amplitude as a function of time, generated by a numerical integration of Eqn (1)

on the emission time. Recent measurements using time correlated photon counting techniques have shown a diversity of emission times depending on gas contents, with some emission times as long as 350ps. Another observed property was the enhancement of the light emission by the doping of water with a small concentration of noble gases such as Ne, Ar, and Xe. It was also observed that the cooling of liquid to near freezing resulted in an increase in light emission by a factor of 6.

B. Acoustics of the (1,1,3) mode:

The resonance frequency is not arbitrary, and is determined in the following manner. A bubble can only sonoluminesce if it is trapped by the acoustic field at a pressure anti-node. The frequencies at which this will occur are dictated by the size and shape of the cavity. Thus, starting from the basic acoustic wave equation we have:

$$\nabla^2 P = \frac{1}{c^2} \frac{\partial^2 P}{\partial t^2} \quad (4)$$

where the acoustic pressure variation is given by:

$$\delta P = \delta P_0 X(x)Y(y)Z(z)T(t) \quad (5)$$

and where the time dependence varies harmonically as:

$$T(t) = e^{i\omega t} \quad (6)$$

Expressing in rectangular coordinates:

$$\frac{1}{X} \frac{\partial^2 X}{\partial x^2} + \frac{1}{Y} \frac{\partial^2 Y}{\partial y^2} + \frac{1}{Z} \frac{\partial^2 Z}{\partial z^2} + \frac{\omega^2}{c^2} = 0 \quad (7)$$

Therefore, the general solution is of the form:

$$P \approx \sin(k_x x) \sin(k_y y) \sin(k_z z) \quad (8)$$

In the above equation the sine is chosen when the boundary is a pressure release (i.e. not rigid). Therefore, to satisfy these boundary conditions at the cell walls we impose restrictions on the values of k_x , k_y , and k_z , such that $k_x = n_x p/L_x$, $k_y = n_y p/L_y$, $k_z = n_z p/L_z$; where $n_{x,y,z} = 1, 2, 3, \dots$. Although $n = 0$ is allowed, this will not generate a pressure gradient and is thus discarded. The resonant frequencies for trapping a bubble are then given by the expression:

$$f = \frac{c}{2\pi} \left[\left(\frac{n_x \pi}{L_x} \right)^2 + \left(\frac{n_y \pi}{L_y} \right)^2 + \left(\frac{n_z \pi}{L_z} \right)^2 \right]^{1/2} \quad (9)$$

where L_x , L_y , and L_z are the dimensions of the cell and c = speed of sound in water (this will vary with temperature). Putting in the values of $(n_x, n_y, n_z) = (1, 1, 3)$ implies that the resonance frequency will be close to 28 kHz and that there will be three pressure anti-nodes in the Z direction and one pressure anti-node in the X and Y directions. Further examination of the solution will reveal that the second pressure anti-node located at the center of the cell will be 180 degrees out of phase with the first and third anti-nodes located near the top and bottom of the cell. The solution looks very much like a standing wave on a string, but in 3 dimensions.

C. Quality Factor Determination

The rectangular cell is able to build up sufficient pressure amplitude to trap the bubble through resonance enhancement of the pressure amplitude. We can crudely think of the dynamics of the acoustic pressure as a 3-dimensional extension of a driven damped harmonic oscillator. In the case of a driven damped harmonic oscillator, x can be expressed as:

$$x = \frac{X_0 e^{i\omega t}}{Z_m} \quad (10)$$

where

$$Z_m = \sqrt{R_m^2 + (\omega m - s/\omega)^2} \quad (11)$$

In this case, m is the mass, s is the force constant, and R_m is the damping term. The sharpness of the resonance is denoted by the quality factor, Q , which is defined as:

$$Q = \frac{\omega_0}{\omega_2 - \omega_1} \quad (12)$$

where ω_1 and ω_2 are the frequencies below and above the resonance frequency at which the average power is one half that at resonance. The rectangular cell in this experiment has a $Q \approx 200$. Since the power is proportional to the pressure squared, the frequencies ω_1 and ω_2 will occur when the pressure is $1/\sqrt{2}$ of the peak pressure amplitude.

II. INSTRUMENTATION

Ultrasonic Horn

In order to set up a standing acoustic wave in the cell, it is necessary to deliver acoustic power with sufficient amplitude to the volume of water. This is accomplished with the ultrasonic horn. Internally, the horn contains a series of annular shaped disc transducers which are bolted to the base. The basic structure and shape of the horn is designed to efficiently couple the pressure waves generated from the transducers to the narrow stem of the horn. All of the transducers are the same. They consist of a ceramic material which has been prepared in such a manner to have permanent polarization. In other words, what we have is a specialized capacitor. As a charge is placed across the capacitor, there is a force generated across the ends as the capacitor wants to separate. Since the transducers are compressed, the repulsive force does not physically expand the disc, but does produce a dynamic pressure. As the charge across the transducer is reversed there is now an attractive force which results in a negative pressure amplitude.

In order to achieve the desired pressure levels, six of these transducers are placed one on top of another and connected electrically in parallel. Acoustically this is equivalent to connecting the devices in series. Collectively the 6 ceramic disc capacitors have a total combined capacitance of approximately 11 nF. In order to efficiently couple electrical power into the transducers, it is advantageous to connect an inductor in series to achieve electrical resonance as given by the simple formulation: $\omega L = 1/\omega C$

Rectangular Cell

In our case, the cell is a plastic container mounted on an electronic box. Epoxied to the container is a small transducer, which will serve as a microphone and will be used to detect when the cell is in resonance.

On one side of the case there are three connectors. The BNC connector on the bottom is attached to the cell transducer, and on the top there is a gray 5 pin Neutrik connector which attaches to the back of the main control box. This cable supplies current to the Peltier Cooler. Please note there are two entire cell setups (cell plus electronic box) in the lab. The cubic cell has a Peltier Cooler, while the tall skinny cell does not. The equations in this document refer to the tall skinny chamber, but you can experiment with both.

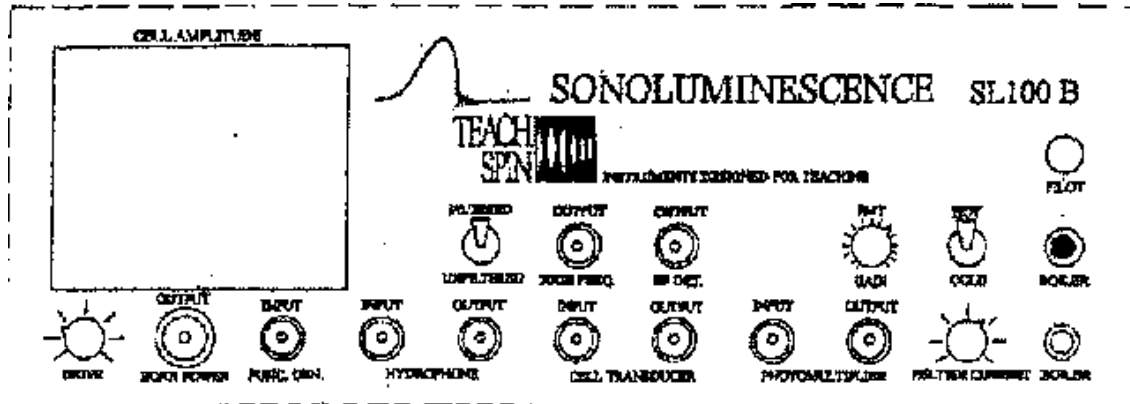


Figure 2: The front panel of the control box

Control Box

Horndrive:

The control box has a high voltage amplifier used to drive the horn. The DRIVE control, on the far left of the panel, controls the amplitude sent to the horn. Next to that is a TNC connector labeled HORN POWER OUTPUT, which can only be connected to the top of the horn(DO NOT CONNECT THIS ANYWHERE ELSE, IT IS A HIGH POWERED OUTPUT). Next to the HORN POWER OUTPUT is function generator input, labeled INPUT FUNC. GEN.

Cell Transducer:

The next section contains four BNC connectors and is labeled, on the bottom, CELL TRANSDUCER. The connector in the bottom left quadrant is labeled INPUT and accepts the input signal from the transducer attached to the cell. After the input, the signal is passed through a filter to eliminate 60Hz noise, it then goes to other stages which process the signal further. The next 3 connectors are outputs which have processed the signal in a different manner. To the right of the input connector in the lower right quadrant is the OUTPUT which simply passes the complete signal directly to the output. This allows one to view a signal produced from the transducer which contains the fundamental as well as the high frequency component that is present when a bubble is trapped. This output is used most often because it allows continuous viewing of a single signal that contains information on the level of acoustic drive pressure in the system, as well as the magnitude of acoustic emission from a trapped bubble. The next output is labeled HIGH FREQ. OUTPUT, which filters the signal

from the cell transducer with a 5th order high pass filter with a corner frequency of 150 kHz. The last connector located in the upper right quadrant is labeled HF DET. OUTPUT and simply uses a peak detector to measure the maximum level of the high frequency output. This peak detector has a 0.1 second time constant; which allows the output to change as the average overall peak value changes with driving amplitude or frequency, but will not change over a single period of the acoustic frequency.

III. THE EXPERIMENT

To begin, make sure the main control box is off and no cables are attached to the front of the unit, or to the cell box.

Degas the Water:

1. If you want to cool your water (which is not necessary), obtain a bucket of ice from Chemistry. There is a dispenser outside where PSBN and Chemistry meet.
2. Fill a flask with 450 mL deionized water. These flasks should be available in the room, if not ask a TA.
3. Place a rubber stopper on top of the flask.
4. Locate the Vacuum Pump and desiccant. The desiccant should have two tubes coming off of it, one should already be attached to the vacuum pump. Connect the other tube on the desiccant to the spigot on the flask.
5. Place the flask in the bucket of ice (if you got one, otherwise just place it on the counter). Make sure no ice is near the spigot or stopper area, you do not want to suck up water through the vacuum pump! Alert a TA immediately if this happens.
6. Switch on the vacuum pump, allow it to pump for 15-20 minutes.
7. To open the flask, slowly wiggle the stopper out. If this is done too fast the water will regas and you will have to degas again. Disconnect the tubing from the flask.
8. Degassed water lasts about 2 hours, prepare another flask to have at hand after the first is unusable.

Setting up the Cell:

1. Carefully pour the degassed water into the cell, try to avoid making bubbles. For the tall skinny cell fill it 10cm high (there is a small mark on the side of the cell).
2. Lower the stem of the horn approximately 1 cm into the water.

Setup the Frequency Generator:

1. The system is designed to accept a signal level of 1 V peak amplitude (2 V peak to peak) from an external frequency generator. A voltage larger than this could damage the transducers.
2. Disconnect all cables from main unit, turn the DRIVE knob on the main control box fully counterclockwise.
3. Turn on the main control box using the switch on the back of the unit.
4. Connect the output of the function generator to the input labeled CELL TRANSDUCER INPUT. (This is only a temporary connection to set the right output level of the function generator.)
5. Set the frequency to a value of 28 kHz and adjust the volume of the function generator until the level of the analog dial on the main control box reads 4 volts.
6. The volume of the function generator is now set. Do not adjust this knob again, instead use the DRIVE control on the main control box to adjust the amplitude sent to the horn.
7. Now that the volume is correctly set, disconnect the function generator from CELL TRANSDUCER INPUT and attach it to FUNC. GEN. INPUT

Connecting the Apparatus:

1. Connect the cable from the ultrasonic horn to the threaded TNC connector on the far left of the main control box.
2. Connect the rest of the apparatus as shown in Figure 3.

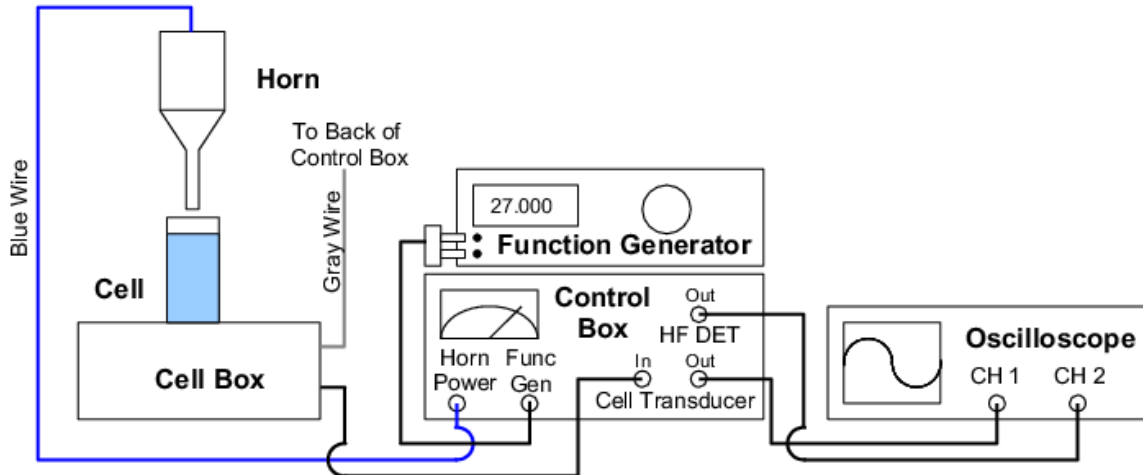


Figure 3: The final setup of the experiment.

Determining the Resonant Frequency:

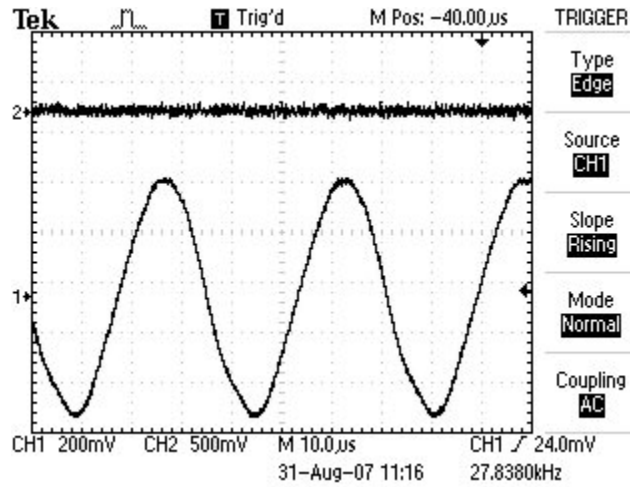
1. With the horn in the water, slowly turn the DRIVE up half way (12 o'clock).
2. Autoscale the oscilloscope, you should see a sine wave in Channel 1. If not, you may have triggering issues (trigger on Channel 1, trigger level just above 0 Volts)
3. Using the large knob on the frequency generator, adjust the frequency in small increments to peak the sine wave. As you approach the resonant frequency, the sine wave should grow in amplitude and then decrease after you have passed it.

Trapping a Bubble:

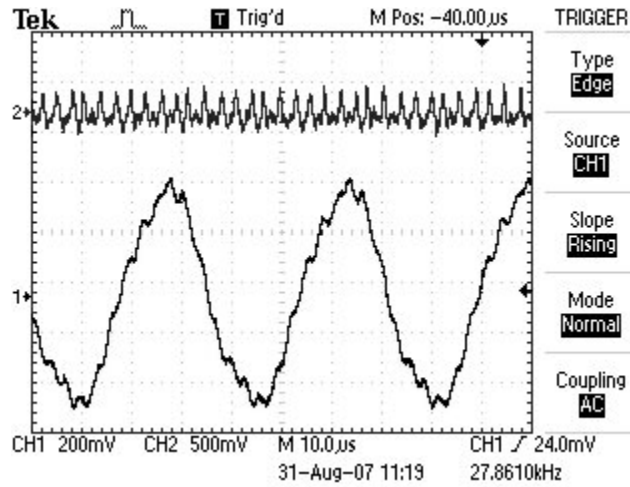
This step requires a certain amount of finesse. You might want to practice this once or twice with the lights on, then turn the lights off when you know what is going on.

1. We will be using an Argon source to seed and trap bubbles.
2. Open all of the valves on the Argon tank except for the final lever near the nozzle.
3. With the DRIVE turned all the way down, insert the Argon nozzle into the water, being careful to not touch the sides of the cell.

4. Open the valve for a split second (bubbles should come out, if not check to make sure the other valves are opened correctly), then remove the nozzle from the cell.
5. Slowly ramp up the DRIVE knob while observing both the oscilloscope and the cell. If done correctly the output of the oscilloscope should resemble that of Figure 4(b) and you should be able to see 1-3 small bubbles glowing blue (when the lights are out). This is difficult to obtain because the output level of the horn has to be exactly right: not enough power and the bubbles will not sonoluminesce, too much and they extinguish.
6. If you don't see anything, try ramping the drive down and seeding more bubbles. It can often take a number of trials before you get stable sonoluminescence. You can also experiment with horn location (make sure the horn is always submerged when driving it!), water level, and water temperature.



(a) No bubble present.



(b) Bubble trapped, notice that the trapped bubble signature has been superimposed on the original fundamental.

Figure 4: The upper trace on each image corresponds to the high frequency output, the lower trace shows our fundamental signal.

IV. QUESTIONS

1. Discuss the steps taken to achieve sonoluminescence. (Document your procedure)
2. Document the range of conditions in which sonoluminescence was achieved. (Temperature, amplitude, frequency, . . .)
3. Measure and document the resonance frequency as a function of temperature.
4. Graph the peak amplitude as displayed on the analog panel as a function of driving frequency.
5. Determine the quality factor of your cell by first finding the resonance and noting the voltage that appears on the panel. Adjust the frequency in 10 Hz increments both above and below the resonance frequency recording the value on the panel (or scope) at each frequency. Graph these values on a linear plot.
6. Determine the velocity of sound in water (as a function of temperature) through your experimental results. Be sure to included a measurement of the error in this calculation.
7. Include printouts of the oscilloscope output when experiencing sonoluminescence.
8. Discuss at least two current theories of sonoluminescence.