Conditions for Sonoluminescence

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Abstract

Sonoluminescence is the emission of visible light when a bubble trapped underwater by ultrasonic waves at resonance collapses from pressure at antinode points. This phenomenon is not fully understood, so our goal is to find out which techniques for producing sonoluminescence work best, to enable more successful future testing. We also measure sonoluminescence brightness under different conditions. To accomplish our goal, we vary water temperature, sound wave frequency, and sound wave amplitude. We found that sonoluminescence is most easily achieved in water below 3^{o} C, and by varying the amplitude of the sound waves while producing bubbles. Varying the amplitude affects the displacement position of the antinodes, which suggests that sonoluminescence is most affected by the pressure that causes bubbles to collapse and expand, which agrees with the results of other experiments.

I. Introduction

Sonoluminescence, the process in which a bubble continuously collapses and expands due to acoustic pressure, during which it emits a visible light, was first announced 84 years ago[1]. Despite several advancements in understanding sonoluminescence, there are still many gaps in the knowledge of why light is produced in the bubble's collapsing stage. Further data on the physical properties of the bubble's environment and the conditions leading up to sonoluminescence could increasing understanding of how sonoluminescence works.

The first recorded instance of sonoluminescence occurred in 1934, when H. Frenzel and H. Schultes observed a photographic plate becoming dimmer underwater when exposed to acoustic waves[1]. The plate was not darkened directly by sound, but rather due to cavitation, a process in which gaseous "voids" in a liquid are generated during changes in pressure. These voids can collapse, emitting a large amount of energy in the process, even enough to produce visible light.

There are two types of sonoluminescence. The first type, the type that affected Frenzel's and Schultes' plate, is multiple-bubble sonoluminescence (MBSL), which occurs when there are multiple bubbles in close proximity undergoing sonoluminescence. The nature of MBSL made it difficult to properly analyze sonoluminescence—MBSL involves groups of bubbles with varying physical properties, and their proximity leads to interactions that can make individual analysis difficult[2].

Fortunately, in 1988, Felipe Gaitan[3] discovered the process for producing sonoluminescence in a single bubble, known as single-bubble sonoluminescence (SBSL). This discovery allowed for a considerably improved environment for analyzing sonoluminescence. Gaitan's procedure was to produce a bubble through cavitation and catch in a standing acoustic wave. At this point, a slow increase of the wave's amplitude would cause the bubble to undergo SBSL.

Several breakthroughs in understanding sonoluminescence have been made by a group led by Seth Putterman, based out of University of California, Los Angeles. Notable achievements include creating a high-precision radius-time curve for SBSL[4,5] and measuring the electron density inside a collapsing bubble[6,7].

Despite many advances in understanding of how sonoluminescence works, the exact mechanism behind the production of light is still unknown. A paper published in 2002 suggests that it is due to the high pressure of a collapsing bubble ionizing the gas inside[9]. Another theory is that the bubble is a vacuum, which in quantum theory contains virtual particles, and that the light is generated by virtual photons becoming real photons[8]. Experiments have shown that the inside of a bubble contains spherically symmetric balls of plasma when sufficiently compressed by acoustic pressure[6,7].

The inability to completely test these theories suggests that the techniques for producing and observing sonoluminescence could be improved. Our goal is to attempt to produce sonoluminescence and measure its light intensity under a variety of conditions. By recording which of the conditions work best, we hope to improve sonoluminescence techniques so that future experiments studying the underlying light-production mechanisms will be more successful. We will vary conditions such as temperature, gaseousness of the water, and the frequency and amplitude of the acoustic waves.

II. Methods

The equipment in the lab setup can be separated into two groups. The first group contains the materials necessary for producing sonoluminescence. The second group contains instruments useful for observing either the process of sonoluminescence, or properties of the bubble once it is undergoing sonoluminescence.

A water tank is necessary to hold the water and bubble. A wire loop that can be heated up by applying current to it is used to produce bubbles. To generate an acoustic wave to trap and collapse the bubble, an ultrasonic horn is used. The frequency and amplitude for the acoustic wave can be set using a function generator. Additionally, the amplitude of the acoustic wave can be driven using a control box from a sonoluminescence kit. To find the positions of the antinodes, a probe attached to an oscilloscope can be put into the water while the ultrasonic horn is active; if setup correctly, the oscilloscope channel set with the probe will show a horizontal line normally, but deviate strongly when at an antinode. A diagram showing a sample standing wave being generated by the ultrasonic horn is shown below.

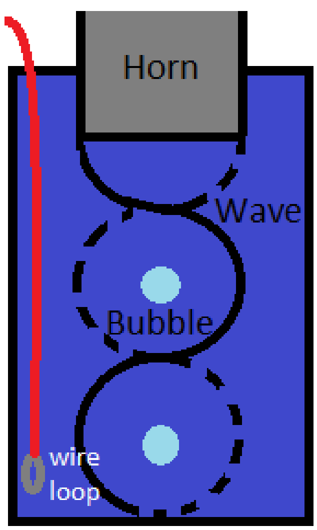

Figure 1. Diagram of ultrasonic horn and its standing wave. When heated, the wire loop generates bubbles that become trapped in one of the antinodes.

Several additions to this setup are used to better observe sonoluminescence. As bubbles in sonoluminescence are relatively small and dim, they are easier to observe using a microscope. We also have a “claw” contraption to hold and adjust the position of the microscope, but any type of microscope capable of focusing on a bubble in the tank would work equally as well. A HeNe laser can be used to scatter light off a bubble which can help with several measurements, such as calculating bubble size. To observe and quantify the amount of light a bubble is emitting, a photomultiplier tube (PMT) can be used; there is also an additional claw to hold it if necessary. The control box is used to control the PMT and to link the various equipment parts together. The oscilloscope can also be used to observe the frequency and amplitude of the acoustic wave and is used in conjunction with the PMT to measure a bubble’s brightness. A high-pass filter can also be set to monitor the frequency in the water cell and block out other signals to determine when a bubble is trapped, since the bubble will be oscillating. We also have a “hood” blanket to put over the water tank area—since sonoluminescence is very dim, it is easier to see the light in a dark environment. The entire lab setup is shown in the Figure 2 schematic below.

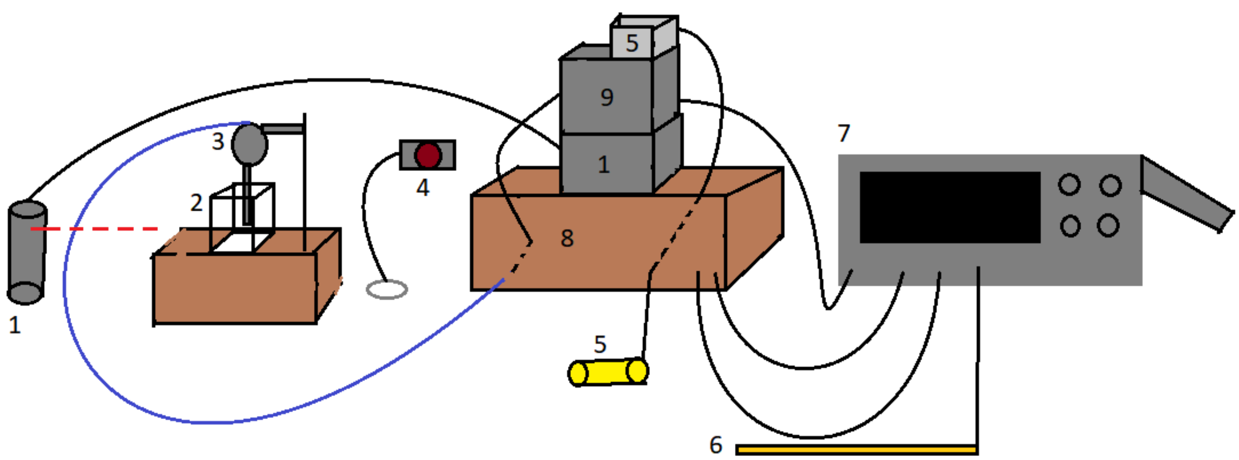

Figure 2. Lab Setup (1. Laser, 2. Water Tank, 3. Horn, 4. Boiler, 5. PMT, 6. Probe, 7. Oscilloscope, 8. Control Box, 9. Function Generator). The water tank (2), horn (3), wire (4), probe (6), oscilloscope (7), Control Box (8), and Wave Function Generator (9) are used to setup a sonoluminescing bubble, while the laser (1) and PMT (5) are used to gather data on sonoluminescing bubbles.

The procedure for creating a bubble and getting it to achieve sonoluminescence is as follows. First, we prepare the water sample for whatever conditions we are testing. After pouring the water into the tank, we then attach the horn and set its frequency using the function generator. It should be set to a resonant frequency, which in our experiment was usually approximately 26.2 kHz. Using the probe, we then locate the positions of the antinodes and place the boiler there. At this point, if planning to use the microscope, it is a good idea to position it so that it can see the tip of the probe, as that is where the bubble should end up. We then remove the probe. Activating the boiler should now produce sonoluminescence—the conditions are set such that any bubbles produced should become trapped and compressed.

As part of our experiment, we tried using water of various treatments. The base water used was at room temperature (~26.6^o C), and deionized. To degas water, we put a flask of water on a hot plate and boiled it for roughly half an hour. To cool water, we put the flask in a cooler of ice and waited until it was at the target temperature. There was also a refrigerator for holding degassed water for longer periods of time. We put a thermometer against the side of the flask to check its temperature, knowing that the water inside should be within a degree or two of the thermometer reading. In our experiment, we used water at room temperature, at 8^o C, at 5^o C, and at or below 3^o C.

Bubble brightness could be measured after sonoluminescence was established. To do this, the microscope was set up to view the bubble, and the PMT was set so that its sensor was in front of the microscope eyepiece. The laser was also moved so that it could be turned on to scatter light off the bubble, which would also appear on the PMT. In our experiment, the bubble we had was set at the bottom-most antinode, but any antinode should suffice. We had both the microscope and the PMT held in “claws” so that they would have the same position throughout the experiment.

III. Results

As shown in Figure 3, over four weeks we were unable to achieve sonoluminescence using gassy water or water at room temperature. Water at eight degrees and five degrees did not produce sonoluminescence, while water below three degrees did.

Water Temperature	Gaseousness	Success
26.6	Gaseous	No
26.6	Degassed	No
8	Degassed	No
8	Degassed	No
5	Degassed	No
8	Gaseous	No
5	Gaseous	No
3	Degassed	No
3	Degassed	No
1.7	Degassed	Yes
0.4	Degassed	Yes

Figure 3. Sonoluminescence Success Table

Sonoluminescence was only observed when using water below 3^{o} C that had been degassed. This suggests that the conditions for producing sonoluminescence are strict.

When sonoluminescence was achieved, the frequency for the horn changed on the oscilloscope. Before it was relatively smooth, but while a bubble was undergoing sonoluminescence, the frequency would show spiky distortions. As noted in the methods section, the high-pass filter channel was also used to check for sonoluminescence. In cases where a bubble had been trapped, it would show a frequency in-phase with the ultrasonic horn.

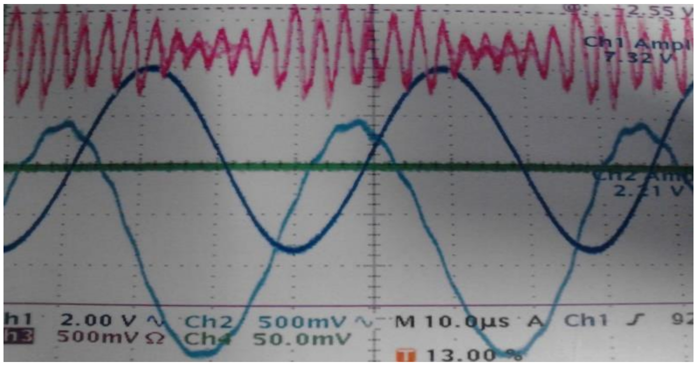

Figure 4. High-pass filter on oscilloscope (pink) while a bubble is trapped—although it has many small oscillations, it also has a very distinct "outer" oscillation that is the characteristic of a trapped bubble

We managed to observe sonoluminescence through a microscope. We took several pictures both through the microscope as well as without a visual aid. Two pictures are shown below in Figure 5.

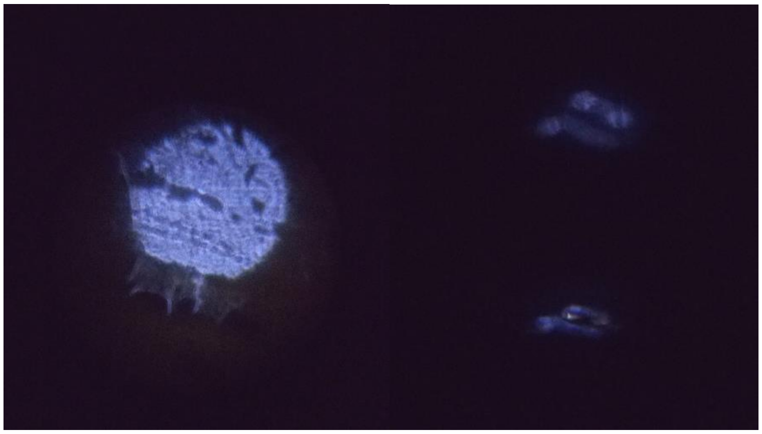

Figure 5. Pictures of sonoluminescence

As can be seen in Figure 5, sonoluminescence looks like a light blue sphere. Figure 5 also shows that it is possible to trap bubbles and have them undergo sonoluminescence at multiple antinodes. Note that in the second picture (right), there is only a single bubble at each antinode, it looks like there are multiple due to a shaky camera.

Another phenomenon we encountered was that sonoluminescence was much easier to achieve when adjusting the amplitude of the acoustic wave while pulsing the boiler to produce bubbles. When moving the amplitude in the range of not audible to barely audible, sonoluminescence was able to be consistently produced.

We took several measurements with the PMT, with and without the HeNe laser. The oscilloscope readings for these measurements are shown in Figure 5 below, with the dropping “peaks” of CH 3 denoting sonoluminescence. In addition to being able to quantify bubble brightness, we also noticed that the measured brightness changed over time. Measurements taken earlier in the lab session had brighter bubbles than those taken later. As we did not change the lab setup once taking measurements, this decrease in bubble brightness is best attributed to the cold water warming up. Once of the earlier readings had a PMT measurement of around 400 mV, while one of the later readings had a PMT measurement of around 9 mV, which shows a very high temperature dependence in sonoluminescence. An additional result of this experiment is that it is likely that sonoluminescence was achieved at temperatures higher than 3^{o} C, although we did not think to check the temperature at the time. This part of the experiment was done much later than the previous parts, and it is not known why we were able to get sonoluminescence at higher temperatures.

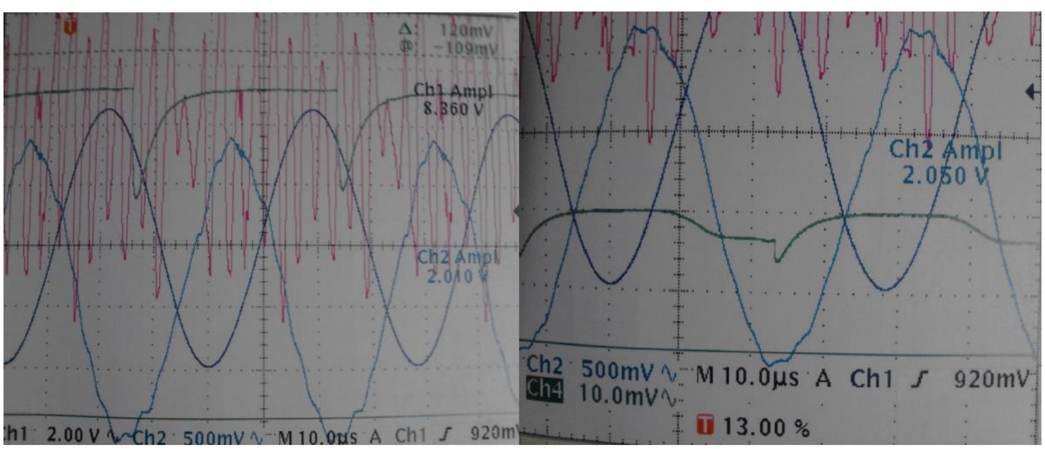

Figure 6. Oscilloscope readings for PMT (green), no laser (left) and with laser (right)

The most interesting observation that can be made from Figure 6 is that the oscilloscope looks completely different when the laser is shined on the bubble. Not only does the PMT reading have a different shape, it is also in a different location. The reading is lower because the laser scattering light off the bubble causes it to appear much brighter. Similarly, the “dip” before the sharp peak can be attributed to the bubble’s changing size. The bubble oscillation is driven by the ultrasonic horn, whose frequency is shown on CH2 (the lighter blue line). Using this, we can infer that the dip occurs as the bubble is shrinking, and that the emission of light by sonoluminescence occurs directly after the bubble has been compressed to its minimum radius.

We also tried dosing water with argon. From previous experiments done by others[10], our expectation was that sonoluminescence produced in this water would be noticeably brighter, as other experiments involving dosing water with a rare gas observe this effect. However, we observed that the bubble was not much brighter than it was in regular water. This could be due to not using enough argon. We were having problems with the PMT when this part of the experiment was done, so a future experiment could involve using the now fixed PMT to measure the differences in readings for regular water and argon-doped water.

There are some possible sources of error in the experiment that should be examined. Due to the qualitative nature of our experiment, errors are less pronounced. The following are possible errors that could have happened during the experiment. Water temperature was recorded before pouring the water in the tank; additionally, the precision of the thermometer used is not known. For this reason, the listed temperatures are assumed to be within a few degrees of the listed values, so the exact temperature of the water when sonoluminescence was achieved may have been slightly higher. There was also no way for us to test the “gaseousness” of the water we used. We let water boil for around half an hour, and additionally checked to make sure that it was not boiling violently, as doing so could suggest that gasses were still boiling out, but these are rather subjective ways to check for gaseousness, so the exact amount of dissolved gas in our water was not known.

Also, due to the large amount of wiring in the control box, there is likely some amount of noise from it showing on the oscilloscope. As we look only at the trends on the oscilloscope, rather than at specific values, it is unlikely that this majorly affects any of the results listed, but it is still worth mentioning.

IV. Discussion

The main goal of our experiment was to check the conditions necessary for sonoluminescence. Sonoluminescence was most easily achievable when using very cold water ($<3^{o}$ C), degassed water, and adjusting the amplitude of the acoustic wave.

This temperature dependence in sonoluminescence has been seen before and our results agree with previous observations. Experiments done by others have shown that the light produced during sonoluminescence will increase in intensity when temperature decreases[11,12,13]. This is theorized to occur due to a lower temperature corresponding to the bubble having a lower water vapor diffusion. This allows for a smaller minimum bubble radius, which means the other gasses inside will be compressed more and achieve a higher temperature, leading to an increase in light intensity.

Along with achieving sonoluminescence more easily in cold water, we also verified the light intensity dependence in our PMT experiment. Although the reason behind why we were able to achieve sonoluminescence at higher temperatures than our initial results would imply is not known, we can theorize. One possible reason is that we have been underestimating the importance of the boiler position, and that since cold water makes sonoluminescence easier to produce, the boiler position matters less in cold water. If the boiler is in an optimal position however, sonoluminescence can be achieved at higher temperatures. This is only a theory and would require additional testing.

The success of sonoluminescence was also based on the gaseousness of the water. We noticed that in gassy water, the oscilloscope reading for the ultrasonic horn was much noisier than when the horn was in degassed water. This can be attributed to the impurities in the water affecting the sound of the acoustic wave. The additional noise may also explain why sonoluminescence was not achieved with gassy water; issues with the acoustic wave could mean that it is unable to properly trap and compress a bubble.

One explanation for the helpfulness of adjusting the amplitude is that low amplitude waves do not compress the bubble enough to start sonoluminescence, and high amplitude waves will pop the bubble. Additionally, the boiler is moved in between trials, and there is no guarantee that bubbles will have a consistent size, so each new attempt at producing sonoluminescence may have a different optimal amplitude for producing sonoluminescence.

We also noticed a distorted frequency when a bubble was trapped. This could be due to the rapidly changing size of the bubble, perhaps in combination with a cavitation effect from the bubble displacing water when in the expansion part of the sonoluminescence cycle.

V. Conclusion

We found that the optimal conditions for producing sonoluminescence are that the water is below 3^{o} C, the water is degassed, and the amplitude of the acoustic wave is adjusted with the drive dial on the control box while bubbles are being produced. We also show that sonoluminescence occurs after a bubble reaches its minimum radius and that its light intensity is dependent on temperature, with colder temperatures equating to brighter bubbles. These results do not provide new information on sonoluminescence but do serve to verify what is already known. Given these results, the next step would be to test additional conditions such as the effect of doping with other gasses. We could also try seeing if the size of the tank has any effect on sonoluminescence.

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