Acoustic Investigation of Liquid Helium

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Abstract

We investigate the properties of the liquid helium, specifically, the acoustics of it. This is an interesting substance because it is a Bose liquid and displays superfluid properties, producing wave motions unlike any other substance. We will be studying around the lambda point of helium, which is the transition point between normal He I and superfluid He II.

Introduction

Theory

We measure the phase velocity of the first, second and fourth sounds through the plane wave resonant mode of cylindrical cavities. On the outside of this cavity, we have an insulated center button that acts as a capacitor microphone, and a loudspeaker on the other side.

To get these phase velocities, we measure the frequencies of the sounds. And then with those phase velocities, we can explore the other properties of the superfluid helium, such as the fraction of the fluid that is superfluid vs normal fluid; and the specific heat.

Apparatus and Procedure

To sustain temperatures low enough for liquid helium to actually transition, we must have a setup that insulates it well enough. The first layer of our apparatus is a vacuum, the next is liquid nitrogen, cooled to 77K. Then there is another vacuum cavity and then the liquid helium is stored in the center.

The more interesting part of the experiment is the cylindrical enclosure within the helium that we will use to test different sounds. The first wave is an ordinary wave, just a sound going through a liquid, and our liquid being helium. To measure the second wave, which is a "temperature" wave, we pierce the sides of the container with narrow slits. This allows us to measure the wave as the superfluid helium flows to hotter regions of the container. To measure the fourth, we create a "superleak". This means that the inside of the cavity is filled with fine powder, giving a certain porosity (of around 40%). Usually, sound cannot propagate through such a finely packed medium, however, superfluid helium can – and we will measure the waves it creates when going through this medium.

Data and Analysis

First Phase Velocity

For the first phase velocity, we simply use the same formula we used in the first experiment. It can be simplified to:

$$f = \frac{c}{2}\frac{n}{L} \tag{1}$$

Solving for the speed, we end up with:

$$c = 2f\frac{L}{n} \tag{2}$$

where c is the speed, f is the frequency, L is the length of the chamber, and n is the mode. In our case, the length of the chamber is $L = 0.0495 \pm 0.0002$ m.

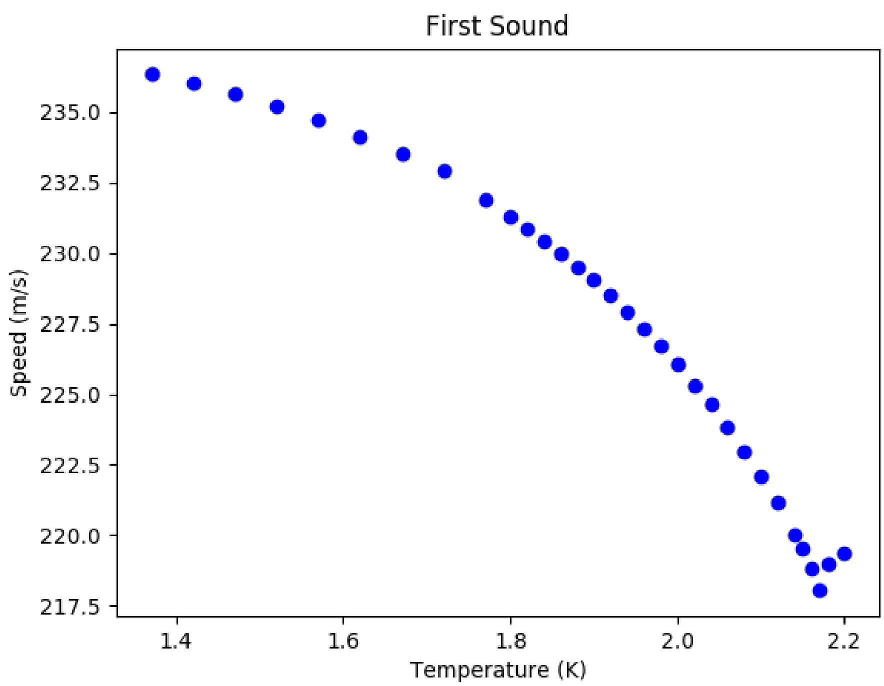

Figure 1: Speed of Sound vs. Temperature for the first sound c_1

Here we can see that as the temperature increases, the speed of sound decreases – until we reach the lambda point around $T = 2.17$ K. At the lambda point, the speed of sound then increases, because normal fluid helium transitions into superfluid helium.

Second Phase Velocity

For the second phase velocity, we do the same thing we did for the first sound.

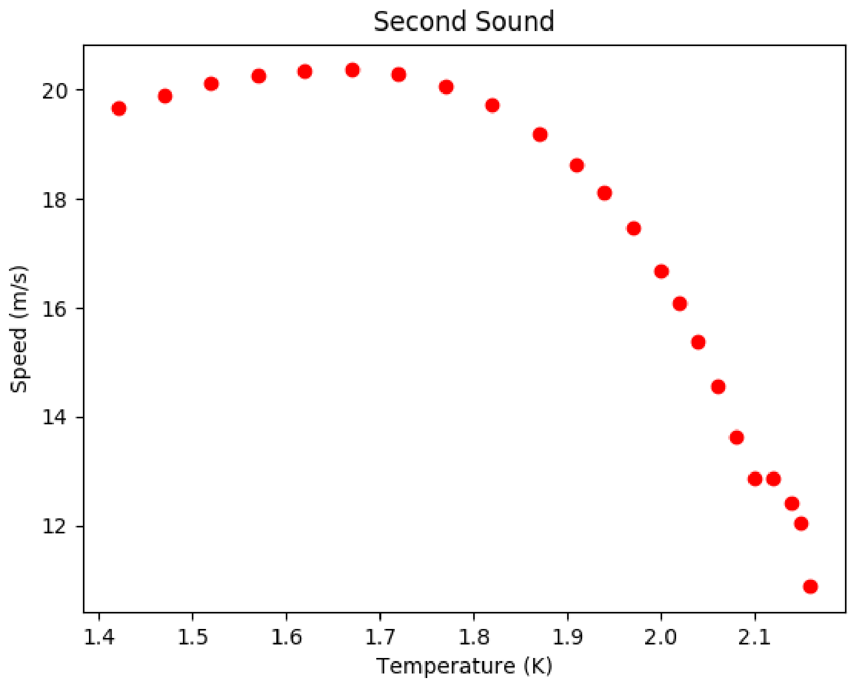

Figure 2: Speed of Sound vs. Temperature for the second sound c_2

As one can see, the second sound increases very slightly before decreasing until the lambda point. What is really interesting about this second sound, is that it is more than 10x smaller than the first or fourth phase velocity. We will discuss these results further later.

Fourth Phase Velocity

To calculate the fourth speed of sound, we had to first find the scattering n. This scattering can be computed from the following relation to the theoretical value of c_4:

$$n = \frac{c_{4,theory}}{c_{4,observed}} \tag{3}$$

By taking our lowest temperature observed value for c_4, we can ensure a data point where the superfluid content is at its maximum. Doing so reveals what the scattering $n = 1.25$. We simply then multiply all of our observed values by this factor, leaving us with this plot:

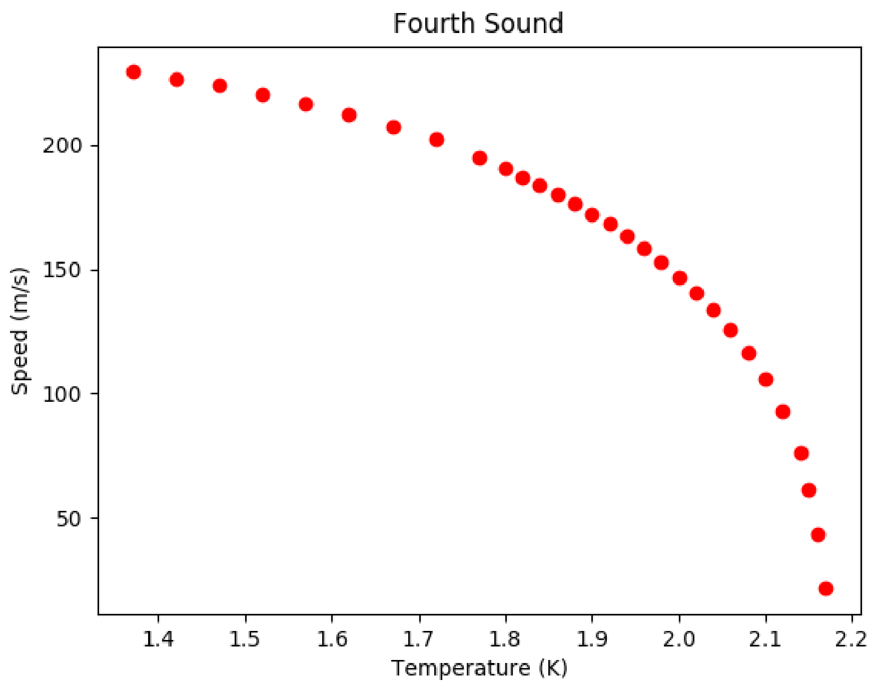

Figure 3: Speed of Sound vs. Temperature for the fourth sound c_4

The interesting part of this plot is that compared to the first phase velocity, the fourth phase velocity drops to a much lower value. We can see the difference in the following plot of the first, second and fourth phase velocities.

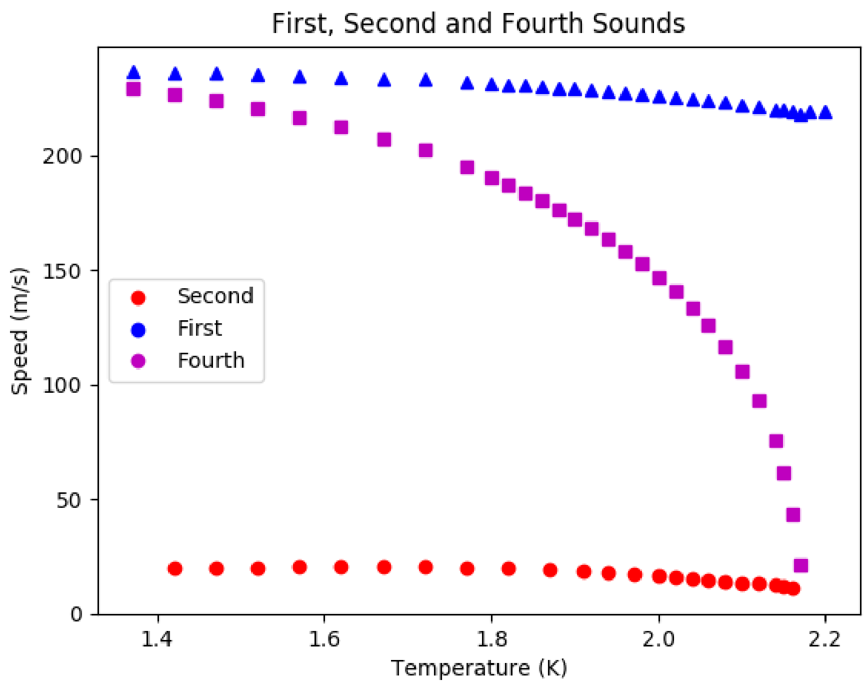

Figure 4: All of the phase velocities in one plot, for direct comparison

Seeing all the plots together really shows the difference between the sounds. The first sound does decrease, but at a much slower rate than the fourth sound. Whereas, the second sound is always very small compared to the first and fourth sounds.

Porosity

The following emperical expression can be used to determine the scattering n:

$$n = \sqrt{2 - P} \tag{4}$$

where P is the porosity of the liquid. In our experiment, this is the helium volume divided by the helium volume and the powder volume combined. We found the scattering in the last section, when determining the fourth speed of sound: $n = 1.25$. From here it is simple to solve for the porosity:

$$P = 0.435 \tag{5}$$

This means that the porosity is about 43.5%.

Superfluid Fraction

The fourth is related to the first speed by:

$$c_4 = \sqrt{\frac{\rho_s}{\rho}} c_1 \tag{6}$$

We can solve for the superfluid fraction ρ_s/ρ:

$$\frac{\rho_s}{\rho} = \sqrt{\frac{c_4}{c_1}} \tag{7}$$

Below is a plot of this value, contrasted with its inverse:

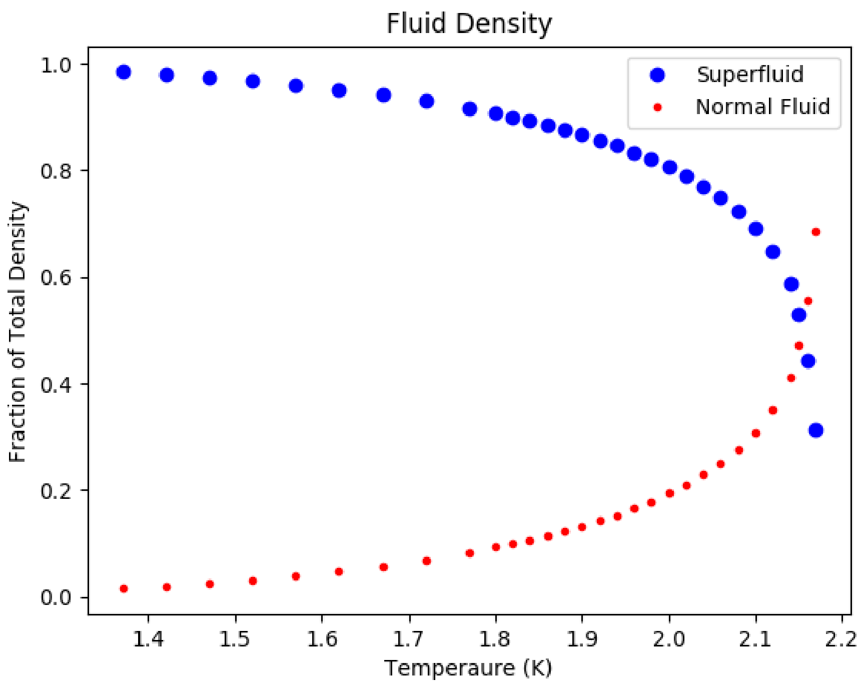

Figure 5: Fractions of Superfluid and Normal Fluid in the Total Density

This value lies between 0 and 1, because it is a proportion. The value ρ_s is the density of the superfluid in the container; ρ_n is the density of the normal fluid in the container. And the total density $\rho = \rho_s + \rho_n$. By dividing the density of the superfluid by the total fluid, we end up with the fraction of the fluid that is superfluid. This can be contrasted with the fraction of the fluid that is a normal fluid to show how the fluid changes as the temperature changes. The normal fluid density is the inverse of the super fluid density: $\rho_n/\rho = 1 - \rho_s/\rho$. This reveals to us that after the lambda point $T = 2.17$, the fraction of the normal fluid begins decreasing, while the super fluid fraction increases. As the temperature lowers even more, the superfluid fraction gets much larger than the normal fluid fraction, as we would expect.

Specific Heat

To calculate the specific heat of our He4, we can use a formula involving the phase velocity of the second sound.

$$c_2 = \sqrt{\frac{\rho_s}{\rho_n}\frac{S^2T}{C_p}} \tag{8}$$

where S is the entropy, T is the temperature, ρ_s and ρ_n are the densities of the superfluid and the normal fluid, respectively, and C_p is the specific heat at constant pressure. Solving for the specific heat, and substituting the value of ρ_s/ρ that we calculated earlier, we arrive at:

$$C_p = \frac{\rho_s/\rho}{1-\rho_s/\rho}\frac{S^2T}{c_2^2} \tag{9}$$

Below is a scatterplot of our data points for the specific heat:

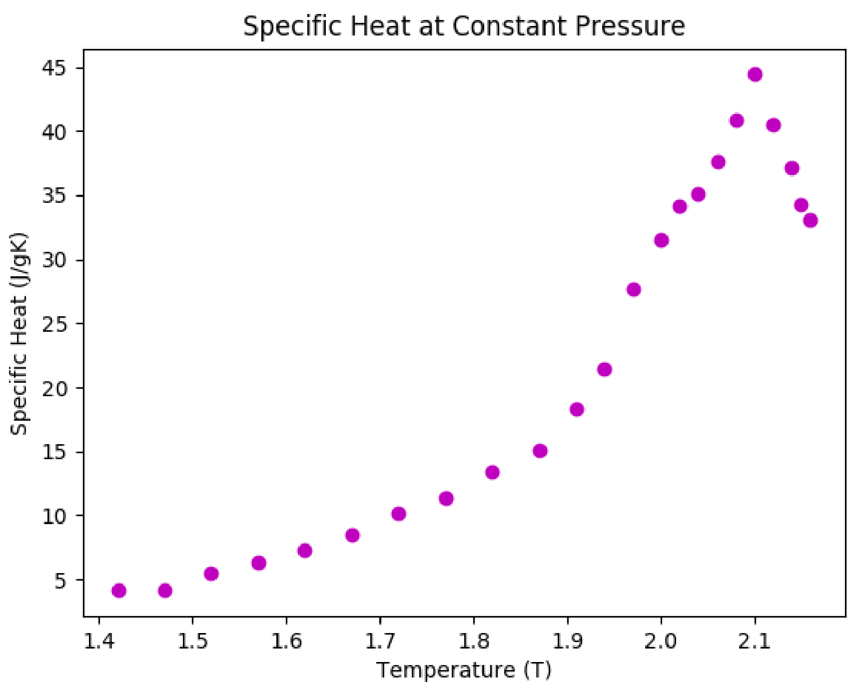

Figure 6: Specific Heat at Constant Pressure calculated from the second sound

The last couple points of this graph don't seem to follow the trend, especially when compared to the specific heat data appended to the lab manual. I couldn't exactly figure out what was going wrong, but I have some possbile ideas. It may be because the density doesn't match up with the temperature; or that the data has been shifted. There is supposed to be a downward trend, but only after the lambda temperature at $T = 2.17$ K. The data on this graph only reaches 2.16 K, so the descent shouldn't have begun yet. It could also have something to with the fact that I had to manually copy the entropy values from the tables, instead of being able to calculate it from another quantity, like the rest of the data.

Further Discussion

One of the most interesting properties of superfluid helium is because it has zero viscosity, and carries no entropy. This allows for things to happen such as the second and fourth sounds we observed in this experiment – things that normal liquids cannot do because they have some viscosity and entropy. There are quantum mechanic explanations for the unique properties that superfluid helium has, but in this experiment we are only observing the acoustical mechanics.

A prominent theory behind superfluid helium is that of the two-fluid model. Basically, it is made up of two independent fluids, normal fluid helium and superfluid helium. We observed properties of this model when we calculated the superfluid fraction, and saw how these ratios changed as the temperature changed.

The first sound wave is a pressure-density wave. It is the same as a classical fluid wave. Basically, the superfluid and the normal fluid move together with the same phase velocity.

The second wave is a temperature-entropy wave. This is very interesting because such a thing does not exist for a normal wave. Due to quantumal mechanical properties, heat transfers by wave, rather than by diffusion like normal. Though I have a very abstract level of understanding of this sound, I will try to explain. Recall that there are two fluids in this contraption, the superfluid and the normal fluid. As we cool down, instead of diffusing the heat, the superfluid will rush to warmer spots, replacing the normal fluids. This happens repeatedly, causing the wave-motion of heat we are observing.

The fourth wave of course involves the finely packed medium. This medium restricts the normal fluid, such that it cannot flow through; however, the superfluid that has no viscosity, easily flows through it. As we can tell with the graphs, as the temperature decreases, and thusly the proportion of the fluid that has transitioned to superfluid increases, the fourth wave increases until it resembles the first wave. At this point, most of the fluid will be superfluid, and most of it can flowly freely through the packed medium. This makes sense, especially when considering that the scattering depends on the porosity.

The heat capacity is interesting because although it spikes very high around the lambda point, it quickly drops off drastically. This means that as more of the fluid transitions into superfluid helium, its heat capacity is lowered. This makes supercooled helium one of the best conductors of heat. Heat is a problem is many engineering tasks, and in all machines – superfluid helium could help solve this problem by moved heat from one area to another. In daily life, things such as water-cooled computers are a thing. Water heats up in one area, flows to a cooler area, then flows back as more warm water rushes in. If one were able to easily and consistently use superfluid helium for something like this instead, one would have solved many mechanical problems engineers face.

Conclusions

In conclusion, this experiment let be observe properties of a fluid I had never interacted with before. I had heard of things called superfluids, but never really understood their properties, or why they act like they do. Although I did not learn in depth about why superfluids exist, I did pick up an abstract understanding of why they do. I did, however, learn a lot about the superfluid, but understanding the different sound modes, and their different setups (i.e. the second wave with the narrow slits; the fourth wave with the finely packed medium). Observing the heat capacity really inspired me for the application of such science into the technological world. However, I also reminded myself that helium is scarce on our planet, but perhaps when we have lunar stations mining helium, we will have a much easier time using this material to its maximum potential.

Were I to re-do this experiment, I would focus more heavily on the heat capacity aspect, especially trying to understand where I went wrong in the calculations.

When excitedly talking about this experiment with my father over the phone, he asked a lot of questions I did not know the answers to – but after writing this report, I'm ready to call him up again and teach him about the interesting properties of superfluid helium!

References

[1] Experiment 4 Lab Manual

[2] The Physics of Superfluid Helium by W.F. Vinen

`https://cds.cern.ch/record/808382/files/p363.pdf`

[3] Velocity of First Sound in He3-He4 Solutions by B.N. Esel'son, N.E. Dyumin, E.Ya. Rudavskii and I.A. Serbin

`http://jetp.ac.ru/cgi-bin/dn/e_024_06_1126.pdf`

[4] Experimental Determination of the Fourth Sound Velocity in Helium II by Kenneth A. Shapiro, Isadore Rudnick

`http://pages.physics.cornell.edu/p510/w/images/p510/b/bf/SS11_Shapiro.pdf`