Superfluid Vortices in Helium 4

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Our group set out with the goal of studying vortices in superfluid He-4. To achieve the superfluid state we used a He-3 cryostat and a He-4 dewar to bring our system to 300 mK. We were primarily interested in studying Kelvin waves after a vortex pinning event. Due to many complications in our experimental setup, we were unable to take data.

I. BACKGROUND

A. Vortex Physics

Vortices occur in many everyday phenomena. Examples include turbulent air flowing off of airplane wings, the ocean water in a whirlpool, and the water flowing out of a bathtub [1].

Vortex physics is applicable in meteorology for understanding air convection and tornadoes, as well as in the cosmological study of neutron stars. Understanding vortex dynamics can also contribute to the ongoing pursuit of a rigorous theory on superfluid dynamics [2].

The study of vortex physics allows us to understand everyday phenomena in our world while simultaneously leading the way to new and interesting applications.

B. Superfluid Helium

Our experiment uses superfluid Helium-4 as a medium for studying vortices. Helium-4 transitions into its superfluid state at approximately 2 K. However, we cool our system to 300 mK to reduce noise in our measurements. Superfluid itself has zero viscosity, but in any real system some amount of normal fluid exists in the superfluid state and reducing our temperatures below the superfluid transition temperature allows us to lessen the amount of normal fluid in the cell. Studying the circulation in our system is made simpler by the fact that the circulation is quantized, meaning we see a relatively constant level unless large energy changes occur. Vortex cores in a superfluid also must end at a boundary, thus our vortices extend to the walls of the container we use (as long as we haven't unintentionally created a vortex loop) [3]. A vortex in superfluid also requires a well defined core; for this we use a superconducting wire which will be discussed further in the next section.

II. EXPERIMENTAL SETUP

A. The Superconducting Wire

As was previously mentioned, a superconducting wire is used as a vortex core in the experiment. The superconducting wire is only 17 microns in diameter and spans the length of the container which holds the superfluid helium.

In order to prepare the wire we begin with a bundle of 187 copper insulated wires. We scrape the insulation off of a middle portion of the bundle which is approximately the length of the cell (the superfluid container that the wire must span the length of). After soaking the middle portion of this bundle in nitric acid, we are able to expose the superconducting wires themselves. From this point we cut away 186 superconducting wires to obtain a final product which consists of two ends of copper insulated wire and a middle portion of very fine superconducting wire. The process can be rather difficult initially as it is easy to break the fine superconducting wire. This final product will be inserted in the cell to be used as the vortex core.

B. The Cell

The main body of the cell is a brass cylinder approximately two inches in length and six millimeters in diameter. On the inner wall of the brass tube we glue a stycast bump, the purpose of which will be outlined later. The final assembly of the cell will consist of the brass tube with two stycast caps glued to each end which have the superconducting wire inserted through them. The wire will be under tension and glued onto each stycast cap. Glued to the upper cap will be a brass piece called the base. The base has six screw holes allowing us to attach the cell to the fridge. See figure 1 for a fully assembled cell.

FIG. 1: Here is a fully assembled cell which will be attached to the fridge and filled with superfluid helium.

C. The Vibrating Wire and Magnets

Once the cell is fully assembled and attached to the fridge, a set of two superconducting magnets are placed around the cell. These magnets create a magnetic field through the cell. By running current through the superconducting wire in the cell, a force is generated which pulls the wire out of its equilibrium position. Since the wire is under tension, the wire will vibrate around its equilibrium position once the current is stopped. This vibration within the magnetic field induces a measurable EMF which changes when a vortex is present along the wire. The EMF not only tells us a vortex is present, but also allows us to know how far the vortex spans along the wire. While it is true that a superfluid vortex must have boundary points and extend to the walls of the container, it is not always the case that the vortex extends along the full length of the wire to the top and bottom of the cell. Occasionally part of the vortex can peel away from the wire and span to the wall of the cell. The part of the vortex that is no longer along the wire is referred to as the free vortex. Our induced EMF signal can tell us when we have N=0 which is no vortex, N=1/2 which will involve a free vortex, and N=1 which is a vortex spanning the entire length of the wire. See figure 2 for a photo of the cell attached to the fridge and the magnets.

FIG. 2: Here the cell is attached to the fridge and the cylinder to the right contains the magnets.

D. The Fridge

For our experiment, we use a He-3 cryostat with several cooling steps to reach a final temperature 300 mK. In the first step of cooling, we dip our entire cryostat into a dewar filled with liquid He-4 at 4 K, bringing our system down to 4 K. We then use a siphon line to pull He-4 into our cryostat and pump on it to cool our system to 1.5 K by use of evaporative cooling. At this temperature the closed system of He-3 can begin to condense, allowing He-3 to collect in what is called the He-3 pot. Charcoal in the He-3 pot will begin absorbing the He-3 as the charcoal is cooled near the boiling temperature of He-3. As the charcoal absorbs the He-3, evaporative cooling occurs again, bringing the system to 300 mK.

The main components of the fridge are seen in figure 3; the vacuum can covers the lower portion of the fridge to thermally isolate the cell and various helium pots from the 4 K dewar (vacuum can is not pictured here).

FIG. 3: Our Cryostat

E. Cooling Down

The process of actually cooling the fridge is more time consuming than it may seem, and it requires many careful checks of the system to keep everything in working order.

Before we can begin a cool down, we need to be sure that all electrical connections are working and that our system is leak tight at room temperature. Once a cell is fully assembled it must be leak checked before we can cool down with it. We can leak check the cell by connecting it directly to the leak detector or by attaching it to the fridge, placing the vacuum can over the system, pumping He-4 into the cell, and pumping on the vacuum can with the leak detector. Once a cell has passed its leak check, we must ensure that it is electrically connected to the fridge. We also go through a process of checking all electrical connections running through the fridge.

Once we have confirmed that our system is working properly, we begin to pump the atmosphere out of our system so that we don't develop ice plugs once we cool to low temperatures. We use a mechanical pump to remove atmosphere from the vacuum can, siphon line, and cell. Typically pumping out the vacuum can and siphon line is relatively quick, but pumping out the cell requires several steps. Once we pump on the cell long enough, the pressure becomes too low for our pumping to be very effective. Thus we put a small amount of purified He-4 gas into the cell to increase the pressure, and then pump the cell out again. We go through this process twice to ensure that all atmosphere is removed from our cell. It is important that we purify the He-4 we pump into the cell to be totally sure that no atmosphere enters the system. To purify the He-4, we cool a charcoal trap to 77 K using liquid nitrogen. Since this is near the boiling point of nitrogen and oxygen, the charcoal will absorb these gases but allow the He-4 to pass through.

After our system is pumped out, we add a small amount of He-4 into the vacuum can as an exchange gas to allow our fridge to reach 4 K more quickly once inserted into the dewar.

We use a lift to raise the cryostat and slowly lower it into the dewar. Lowering slowly is important as we don't want too much of our He-4 to boil off as we insert the hot cryostat. This process generally takes something on the order of 30 minutes. Once the fridge is fully inserted we can start the fridge and begin further checks of our system.

III. EXPERIMENTAL GOALS

A. Precession and Vortex Pinning

After the fridge is running and our system is properly working, we can rotate the fridge to create a vortex in the cell. While we never made it this far due to experimental complications, I will still discuss the concepts that we were interested in studying. One issue of interest was to understand more about how to dislodge a vortex from the wire and how to pin a vortex to the bump in our cell. Once part of the vortex is dislodged and we have a free vortex, precession occurs as the free vortex rotates around the cell with the rest of the rotating fluid. As energy dissipates from the vortex, the free vortex can drop to the level of the bump and sometimes become stuck on the bump. This is called a pinning event. Some areas that we found interesting were how the bump size might have an effect on pinning, and how it might affect observable Kelvin waves.

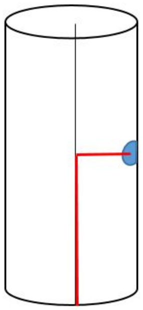

FIG. 4: A schematic of a free vortex pinned to a bump

B. Kelvin Waves

A Kelvin wave is an oscillation of the vortex itself. Students in this experiment had previously observed the first mode of Kelvin waves after a free vortex pinned to the bump. We were hopeful that by using a smaller bump and a slightly more off center wire, we could increase the length of the free vortex and observe higher modes of Kelvin waves. With a longer free vortex, higher modes of Kelvin waves should be more observable because we would potentially be able to see more periods of the waves, thus making them more obvious.

C. Abrupt Temperature Changes

In the summer of 2016, students observed some strange behavior when abrupt temperature changes were made. One goal for this summer was to investigate this further and take more data to see if any trends occurred. While we did some data analysis from 2016, it appeared as though there wasn't a definitive trend and further data would need to be taken.

IV. RESULTS AND FUTURE WORK

Unfortunately we were unable to obtain any data of our own this summer due to many complications in the experimental setup. We spent much of our time diagnosing and fixing issues. Some commonly occurring problems often had to do with the cell leaking or not fitting properly on the fridge, the cell vibrating wire being shorted, wires in the base of the cell breaking, bad solder joints causing our magnets to be unable to persist current, a leak in the vacuum can, and various electrical issues with the fridge and the cables that connected to the fridge. Overall we attempted five cool downs, but many other times were close to cooling down and found problems at room temperature. We are hopeful that enough issues in the experimental setup have been fixed so that future students can successfully take data.

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