Jonas Bylander, November 2004

Laboratory exercise on superfluid helium

Low temperature physics

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In this laboratory exercise you will study some interesting properties of the quantum fluid ^{4}He in its superfluid phase (He II). You will perform experiments that demonstrate the thermomechanical effect, the Rollin film and second sound. These phenomena will be discussed in the context of the two-fluid model.

Before the lab, it is important that you read this memo and the corresponding sections in the textbook, in particular the parts concerning the two-fluid model of superfluidity. For your help there are a few review questions included in the text below.

Properties of superfluid helium

Helium has the lowest boiling point of all known substances: 4.2 K for ^{4}He and 3.2 K for ^{3}He (at atmospheric pressure). It is the only substance that remains liquid under saturated vapour pressure down to absolute zero due to its weak van der Waals forces and small mass that makes its zero point energy considerably high. In this exercise we will study some of the properties of liquid ^{4}He. Figure 1 shows the phase diagram. Upon further cooling, liquid ^{4}He (He I) undergoes a second order phase transition to a superfluid phase (He II) at the so-called λ point at 2.2 K. Helium atoms are bosonic particles, obeying Bose-Einstein statistics. The phase transition at the λ point is a Bose-Einstein condensation, where (almost) all atoms gather in the same quantum state, the ground state. There are always some particles that do not belong to the collective ground state, the so-called quasiparticle excitations. Since all the atoms in the condensate are in the same quantum state, they share a common wave function, and act in a collective way. This leads to unique properties such as flow without viscosity and very high thermal conductivity.

Questions: How can liquid He be cooled from 4.2 K to below 2.2 K? Why is the phase transition temperature called the "λ point"? How do the heat conductivity and heat capacity depend on temperature near the λ point?

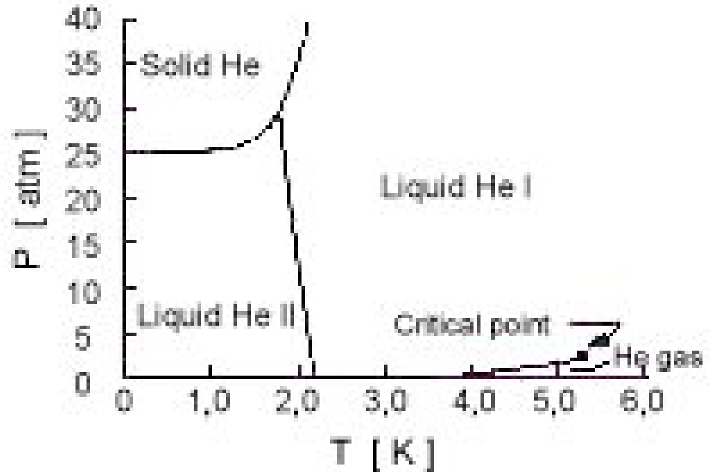

Figure 1: Phase diagram of ^{4}He.

The two-fluid model

According to the two-fluid model, He II behaves as if it were a mixture of two liquids, the superfluid and the normal fluid. The superfluid, of density ρ_S, has zero entropy and flows without viscosity, whereas the normal fluid, of density ρ_N, carries entropy and has viscosity. The total density is constant, $\rho= \rho_S+\rho_N$, but the proportions of superfluid and normal fluid depend on temperature. At low temperature, $\rho=\rho_S$ and $\rho_N=0$, whereas at the λ point, $\rho=\rho_N$ and $\rho_S=0$. A temperature change thus changes the proportions of normal fluid and superfluid. It has to be pointed out that the two fluids cannot be physically separated from one another. A particular atom cannot be regarded as belonging to either the superfluid or the normal fluid. All atoms are identical and the model has to be used to describe the properties of the entire fluid.

Experiments

We will fill a glass cryostat with liquid helium and do the experiments on samples immersed in the liquid. For thermal shielding we will first fill liquid nitrogen in an outer glass cryostat.

The thermomechanical effect (fountain effect)

A small glass container is put in He II so that half of it is below the surface and half is above. The upper end has the form of an open tube, whereas in the lower there is a porous plug, a so-called superleak, that lets through the superfluid but not the normal component of the liquid. When a heater in this plug is switched on, a fountain of He flows out of the tube. **Explain this!**

The superfluid film (Rollin film)

If we fill a bucket with He II and then lift it out of the bath, then it will rapidly become empty again. You will se the liquid dripping from the bottom of the bucket, at the same time as the level in it decreases. **Why?**

The Kapitza spider

A very elegant experiment with He II is the Kapitza spider (Figure 2). The only openings to the small hollow container are the bent tubes. When it is heated by a lamp it starts to rotate as the heated fluid flows out through the arms, propelling it around. But the container never becomes empty; it continues to rotate as long as it is heated by the lamp. **Explain this using the two-fluid model!**

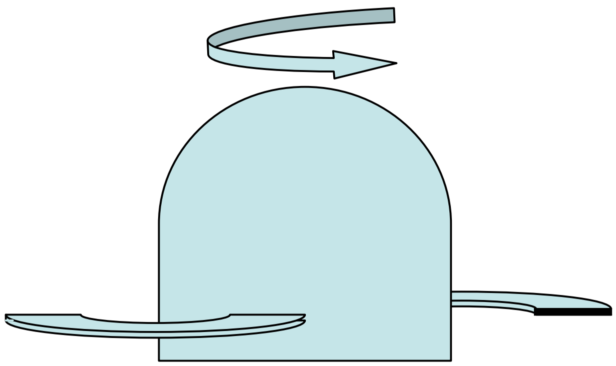

Figure 2: The Kapitza spider.

Second sound

In He II there are two different mechanisms of wave propagation: ordinary (first) sound, and second sound. Ordinary sound is a density wave that propagates through the liquid. For second sound, on the other hand, the density, ρ, in every part of the liquid remains constant. Instead the local value of ρ_S/ρ undergoes oscillations (and correspondingly ρ_N/ρ oscillates in counter phase), we have a wave of temperature or entropy.

In this experiment we will determine the speed of second sound. A tube, partly submerged in He II serves as our measurement set-up (Figure 3). The surface level inside the tube can be varied by pulling the tube up and down. When an alternating current (of frequency 440 Hz) is applied across the resistive heater at the bottom of the tube, the liquid is heated periodically in time, setting up a standing wave in the tube. At the surface, helium boils off and starts a pressure wave (*i.e.* an ordinary sound wave) that is detected by a microphone mounted at the top of the tube. The microphone signal is detected using a lock-in amplifier. The amount of boil-off is proportional to the amplitude of the temperature wave, and by adjusting the height of the He II pillar inside the tube, the wavelength can be determined.
Knowing this, how can the speed of second sound be determined?

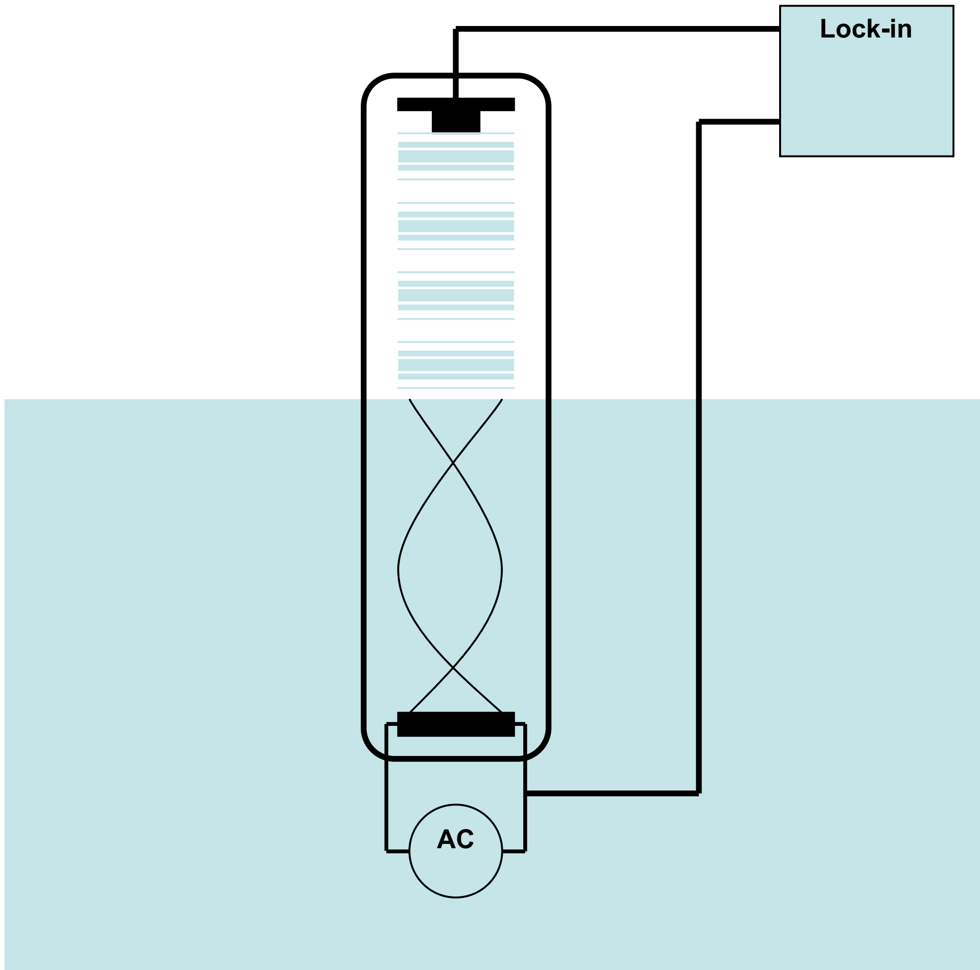

Figure 3: Experimental set-up for second sound measurement.

Task

After the lab, write a report on second sound. Make sure that your report contains a good description of the phenomenon and an explanation within the framework of the two-fluid model. Describe the experimental method and your results. End your report with a discussion. Hand in the report to the supervisor within one week after the lab.