

# E-1 Properties of Superfluid Helium

From Physics 191r

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First experiment: II

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## Learning Goals

- Understand the origin of second sound in superfluid liquid helium.
- Observe the "fountain effect" and cessation of boiling in superfluid helium visually.
- Measure the speed of second sound as a function of temperature.
- Measure the heat capacity of liquid helium as a function of temperature.
- Learn techniques of low-temperature physics.
- Handle cryogenic liquids safely.

## Introduction

This set of experiments provides an opportunity to explore some of the special properties of liquid  $^4\text{He}$  in its superfluid (http://en.wikipedia.org/wiki/Superfluid\_helium#Helium\_II\_state) state (known as helium-II) as well as to be introduced to some techniques of low temperature physics and vacuum pumping or the flow of gases. These strange unusual properties are characteristic of no other substance, and are an effective means for investigating and understanding the nature of this quantum liquid. Quantum liquids are fluids in which the zero-point energy is comparable to the potential energy so that the atoms are weakly localized. One of the unusual properties of helium is that it remains a liquid to a temperature of 0K. The most striking property of He-II is its superfluidity, i.e. its ability to flow without viscosity or dissipation. It is believed that superfluidity in helium is due to Bose

(http://en.wikipedia.org/wiki/Satyendra\_Bose) -Einstein

(http://en.wikipedia.org/wiki/Einstein) condensation ( $^4\text{He}$  atoms are bosons). The isotope He3 is a fermion, and due to pairing of atoms becomes superfluid, but at a much lower temperature than  $^4\text{He}$ , about 3 mK, outside of the range of access in this laboratory (You can consider a pair of fermions as a composite boson. To renormalize your thinking,  $^4\text{He}$  is a composite boson of spin 0; it is composed of 2 protons, 2 neutrons, and 4 electrons, all fermions.)

At approximately 2.2 K, helium undergoes a second-order phase transition from the normal liquid phase to helium-II. This transition is known as the  $\lambda$ -transition and the transition temperature as the  $\lambda$ -point. The name comes from the shape of the specific heat curve and the shape was one of the first indications that liquid helium might have unusual properties. In this experiment one of the properties you will investigate is the specific heat as a function of temperature, the earliest measurements of which were made by Keesom

(http://en.wikipedia.org/wiki/Willem\_Hendrik\_Keesom) in the early 1930's.

Superfluid helium, besides supporting the propagation of ordinary pressure, or "first sound" waves, can also propagate temperature waves. These "second sound" waves are undamped thermal waves displaying all the usual properties of wave phenomenon, including resonance and reflection characteristics (properties inherent in the original thermal standing wave experiments of Peshkov). To have heat flow conforming to a wave equation, rather than to the classical diffusion heat flow equation, results in such seemingly paradoxical situations as heat flowing uphill against thermal gradients. As in other forms of wave propagation, the velocity of second sound as a function of temperature is the most readily measurable quantity associated with the phenomenon as well as the most physically significant.

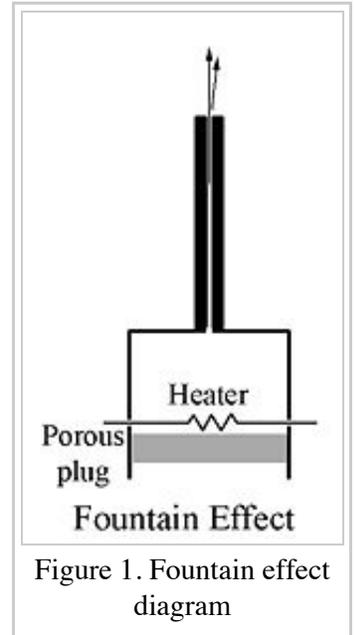


Figure 1. Fountain effect diagram



Figure 2. Fountain effect apparatus

A very useful model for understanding He-II is the two-fluid model (see Tilley and Tilley). Below the lambda point helium can be thought of as being composed of two interpenetrating fluids, the superfluid density  $\rho_s$  and the normal component  $\rho_n$ . Conceptually, the superfluid component has all atoms in the ground state with zero entropy, while the normal component behaves like a normal fluid. Landau ([http://en.wikipedia.org/wiki/Lev\\_Landau](http://en.wikipedia.org/wiki/Lev_Landau)) in his famous 1941 article (see appendix of book by Khalatnikov) interpreted the normal component as excitations (phonons and rotons) whereas the superfluid component is the background ground state fluid. The superfluid component can be determined from the velocity of second sound, the heat capacity, and other parameters.

Below the lambda point helium has the largest thermal conductivity of any substance in nature. This is due to convective flow in which  $\rho_s$  flows towards hotter regions and is converted to normal component. A porous plug sealed into a tube can be made of a finely packed powder such as rouge or a porous glass such as vicor. Normal fluids cannot flow through such a plug, but the superfluid can. Heat is dissipated in a 100  $\Omega$  resistor above a porous plug. Superfluid flows through the plug at a sufficient velocity to form a fountain (see figure). The fountain effect will be demonstrated in this experiment. Another interesting phenomenon (which will not be studied) is film flow. Above the surface of SF helium a thin film (few hundred angstroms thick) will form on the cryostat walls and this film is also superfluid. If a test tube is dipped into the SF helium and withdrawn, the test tube will empty as the film flows up the inner wall and down the outer wall to drip back into the main bath. Why does this happen?

## Apparatus

The experiments are performed in a "superinsulation" cryostat <sup>[1]</sup> equipped with four windows so that you can visually observe the liquid helium during transfers as well as the phenomena associated with the  $\lambda$ -point transition. Lowering the temperature below 4.2 K is accomplished by pumping on the liquid helium with a vacuum pump. Temperature measurements are made with two mechanical manometers <sup>[2]</sup>, a carbon resistor, a germanium resistor that you must calibrate, and a calibrated diode. You will use two different inserts, each in its own cryostat. One is designed to study second sound and observe the fountain effect, the other for measuring the heat capacity. The same mechanical vacuum pump is used to cool either cryostat below 4.2 K.

## Second sound transmitter/receiver

The second-sound wave is produced and detected by means of resistive elements. A pulse of current through the transmitting element (Figure 4-1) (nichrome ribbon <sup>[3]</sup>, 10  $\Omega$ ) produces a temperature pulse in the helium-II. Second sound is detected with a bolometer, a resistor whose value depends sensitively on temperature. The bolometer (Figure 4-2) is a carbon resistor (1/8 watt, 65  $\Omega$  at room temp) whose phenolic insulation has been ground off on one side. Its value can increase to of order 10 k $\Omega$  at 1.5 K. As the temperature wave hits the resistor, it produces a measurable change in resistance. This resistance change is converted to a voltage signal by means of a constant DC current (Figure 5-3) through the resistor. The signal is of the order of microvolts and must be amplified and filtered of noise before being displayed on an oscilloscope. Because of the windows in the cryostat, electrical shielding is poor and electronic techniques for minimizing pickup of noise voltages (which completely swamp the signal) are necessary. The details are discussed below. The carbon resistor detector picks up all kinds of electromagnetic noise (most of which is 60 Hz). It has been wired up as a four-wire (Figure 4-4 and Figure 5-4) detector; one twisted pair (of wires) carries the current while the other pair serves as the voltage leads - each pair is shielded. The voltage leads go to a low-noise differential amplifier, which effectively subtracts the absolute voltages (measured on each side of the resistor), thereby amplifying

only the difference voltage. High and low-pass filters in addition to a 60 Hz band-reject filter further reduce the noise levels before the signal is sent to the scope.

Figure 3 shows a block diagram of the instrumentation.

## Experimental Procedures and Comments

### Cryostat cool-down

In order to provide an environment within the He Dewar in which we may collect liquid He, the Dewar must initially be cooled with liquid nitrogen. It is important to follow the procedures carefully and you should not attempt the liquid He transfer without someone who has done it before (a faculty or staff member). After you become familiar and comfortable with the process you can proceed on your own.

Read Appendix 4

([https://coursewikis.fas.harvard.edu/phys191r/How\\_to\\_Transfer\\_Liquid\\_Helium](https://coursewikis.fas.harvard.edu/phys191r/How_to_Transfer_Liquid_Helium)) in the Lab Manual carefully and view the Liquid Helium Transfer Video

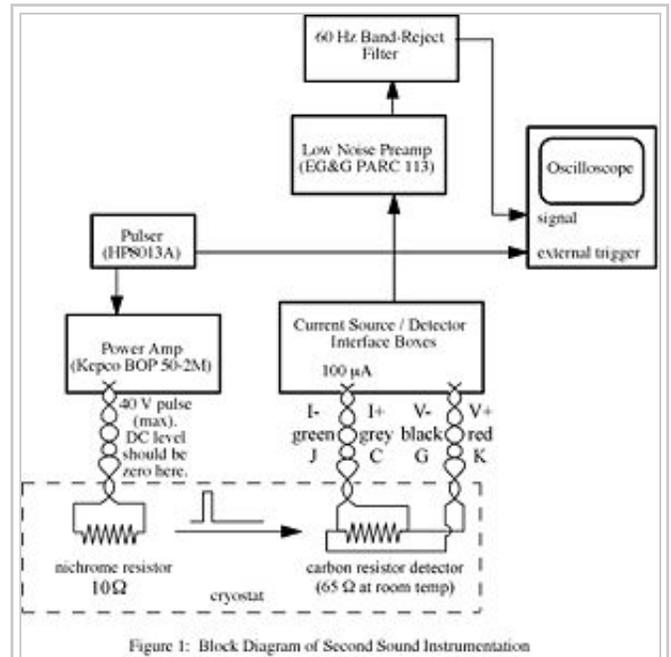


Figure 3. Second sound block diagram

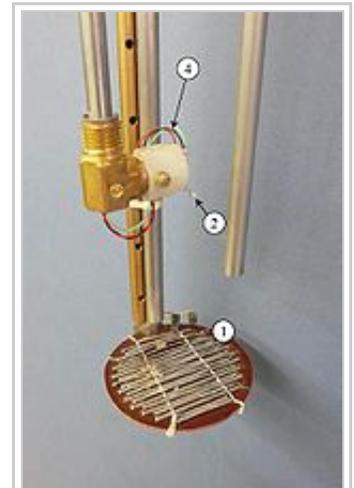


Figure 4. Second sound transmitter and bolometer



Figure 5. Second sound breakout box and DC current source

(<http://stream.fas.harvard.edu/ramgen/permanent/physics190r/LiquidHeliumTransfer.rm>) available on the course web site before transferring helium for the first time.

The temperature of liquid He is 4.2 K at atmospheric pressure (760 mm Hg). The temperature may be lowered through the  $\lambda$ -point by pumping on the liquid He to reduce the vapor pressure and hence cool by evaporation. The procedure is to seal the cryostat by plugging up openings and pumping on the helium. Insert rubber stoppers in the port that accepts the liquid He transfer tube and the liquid nitrogen blow-out tube, close the back-fill valve (lightly), and seal the Tee of the pumping-port with the KF40 end-cap. The pump is isolated from the cryostat by a large valve with a small bypass valve. To cool, start by slightly opening the small bypass valve. Pump slowly for efficient cooling; it should take at least 20 minutes to reach the lambda point. As the pressure is lowered eventually you can partially open the large bellows valve. The system will now pump down through the  $\lambda$ -point. This point may be unambiguously visually observed by the spectacular cessation of boiling in the liquid helium. Why does normal helium bubble and He-II not, when boiling? In order to pump down to much lower temperatures, the large valve must be opened fully. You will find that the helium loss in reaching the  $\lambda$ -point from 4.2 K is typically 1/3 the original volume; at sub  $\lambda$ -point temperatures you should be able to perform experiments for the rest of the lab period with no restriction because of lack of liquid helium, unless you dissipate too much heat with the nichrome heater.

## Helium level detector

It is important to know how much helium is in a cryostat; a sufficient amount must be transferred so that an experiment can be executed in the available time, and the experimenter always wants to know how much more measuring time remains. The easiest method is by visual observation and this can be used when the helium level is in the vicinity of the windows in the cryostat. When the level is higher we use a superconducting level detector for second sound and a capacitance level detector for heat capacity.

The level of liquid helium is monitored in the second sound experiment by a superconducting indicator (American Magnetics model 134 Liquid Helium Level Monitor) connected to a piece of wire (typically a niobium alloy) with a superconducting transition temperature above 4.2 K. The portion of the wire in the liquid helium is superconducting (zero resistance) and the portion above the liquid is normal. The total resistance is related to the proportion of normal wire; a four-lead resistance measurement is necessary. Sufficient power must be dissipated in the wire so that the section in the vapor phase is normal while that in the liquid phase is superconducting. Additionally, there is a heater resistor built into the probe to ensure that a section of the wire above the liquid is warmed above the transition temperature; dissipation in the wire then propagates the normal region down to the liquid-vapor interface. Dissipation in the wire is substantial. Therefore use the INTERVAL mode or turn it off so as not to boil away your helium! Note that the bottom of the sensor is above the bottom of the cryostat; thus a 0% level indication does not mean you're out of helium -- but you can see the level through the window. The "EMPTY METER" measures the cryostat's percent emptiness. Actually, the current supplied by the American Magnetics 134 is applied to the SC wire, and the voltage drop across the wire is monitored directly by a voltmeter (about 22 V when empty and 0 V when full).

## Second sound

By pulsing the heater and observing the delayed arrival of a heat pulse at the resistance thermometer (several centimeters away), measure the velocity of second sound as a function of temperature, varying the propagation distance. Repeat this for the complete range of temperatures accessible to the apparatus.

## Specific heat

Heat capacity (or specific heat) can be measured at constant volume or constant pressure. Our procedure is to fill a small<sup>[4]</sup> cell with helium. The cell is inside a vacuum can, which itself is in the helium bath, shown in

Figure 11a below. The cell is suspended by a fine stainless steel capillary (with low thermal conductivity) so that it can be thermally isolated. It is also equipped with a heater and a germanium resistance thermometer, which is known to retain its calibration if cycled between room temperature and liquid helium temperatures. A known amount of pure helium gas is condensed into the cell from a container with a calibrated volume and pressure gauge. Study the gas handling/pumping manifold on the bench top adjacent to the cryostat. A pump (see Figure 11b below) aids in gas handling, as you will have to evacuate volumes and transfer gases. The storage vessel of helium gas to be condensed and studied is already filled with high purity helium gas. Be careful not to accidentally pump it away or contaminate it.

To initially cool and condense the helium into the cell, the cell must be thermally linked to the pumped bath so that it cools to temperatures substantially below the lambda point. This is done by introducing a small amount of helium gas via the pump-out tube into the vacuum can for thermal exchange. Helium gas is stored in a pressure cylinder. Of order several  $\text{cm}^3$  of He gas at one atmosphere should be sufficient (pressure\*volume is a quantity of gas or atoms). After the helium is condensed the can is again evacuated. (See the section on Pumping the vacuum can). If this is done correctly the temperature of the cell will be very stable and almost independent of the bath temperature. Individual heat pulses are then applied to the cell heater and the resultant temperature rise is recorded.

You are provided with a homemade electronic box that will issue single pulses (Figure 8-1) on command by pushing the red button (Figure 8-2). The pulse time (Figure 8-3) and amplitude (Figure 8-4) are variable. A fixed 1 second, 50 mV reference pulse (Figure 8-5) output is located at the left side panel. Recording this along with temperature is useful to mark the beginning of steps in temperature. When the pulse is inactive, the pulser output would ideally be zero but might show a slight dc level. Use the offset null control (not pictured) on the top panel to tweak the dc level close to zero. Power for the pulser comes from four 6 V lantern batteries (Figure 8-6) configured to supply +/- 12 V. Batteries are used so that the output is fully isolated from ground. Isolated output is needed because the oscilloscope input, connected across the heater "voltage" connection, is ground-referenced. A modified power cord grounds the aluminum chassis of the pulser.

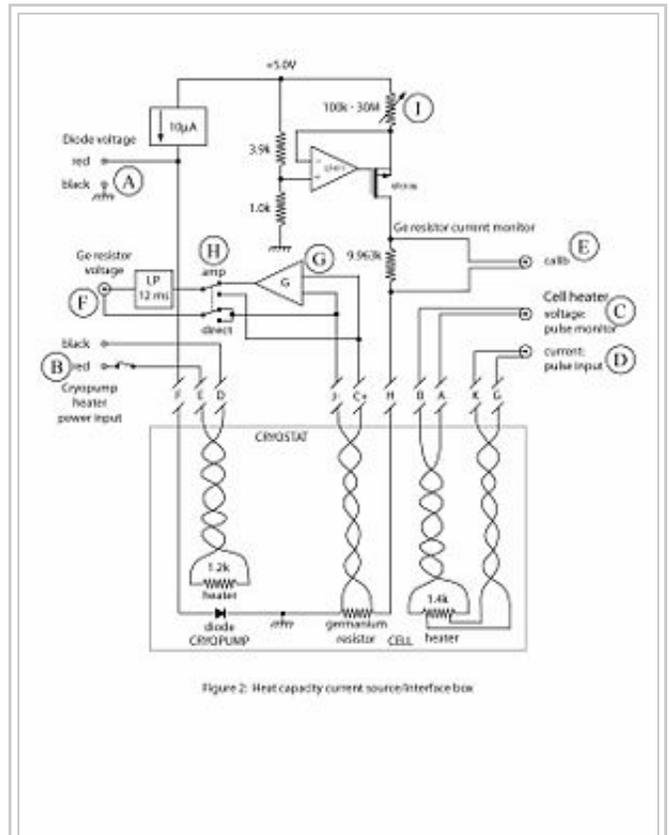


Figure 6. Heat capacity schematic diagram



Figure 7. Heat capacity interface box panel



Figure 8. Heat capacity pulser - panel view

The energy dissipated in the cell can be varied by orders of magnitude by varying the voltage and the length of the pulse. You must determine the value of the heater resistance so that you can calculate the energy transferred to the cell by each pulse. (The heater resistance is connected with 4 wires for accurate measurement of resistance.) This measurement will give the heat capacity of the helium and the cell.



Figure 9. Heat capacity pulser - circuit view

The empty cell is called the addendum. To determine the heat capacity of the helium you will have to measure the heat capacity of the addendum and subtract this off. The addendum is mainly metal (copper). What is the expected behavior of a metal as a function of temperature? To get good results you may have to tailor your pulses in different regions of the temperature. It is useful to record the thermometer voltage on a strip chart recorder to see if the temperature is stable, but for precision you should use the digital voltmeter. A computerized strip chart recorder is available. Use the LabVIEW program, “xt2\_mx.vi” (current version apr09). See the section on the LabVIEW program below for more information.

Note: The small capillary to the cell can get plugged up with contaminants in the He sample (solid air), possibly blocking the path for expansion when the cell warms up (to room temperature). We have built a safety rupture valve onto the cell to prevent a serious accident. A tube connected to the cell is sealed with a thin foil of brass, which will rupture if the pressure gets too high so that the helium can expand into the vacuum can.

### Capacitance level gauge

Another way of detecting the helium level is to use a capacitance level gauge. Two long concentric stainless steel tubes with a very small gap between them serves as the gauge. The tubes are separated by an insulating thread, which prevents shorting. The capacitance of a meter long section is of order 1000 picofarads. We take advantage of the fact that the dielectric constant of liquid helium is about 1.054 and that of gaseous helium is 1.00000+. Thus if the gap between tubes is filled with liquid helium the capacitance will be increased by a factor of 1.054, and intermediate levels will have a proportional increase of capacitance above that of the empty dewar.

In the helium heat capacity experiment, the gauge is 24 inches long. The empty (cold) capacitance is 0.624 nF. When full with liquid nitrogen, the capacitance is 0.888 nF. When full with liquid helium, the capacitance is approximately 0.650 nF. The capacitance is measured with an ESI (Electro Scientific Industries) 252 Impedance meter.

### LabVIEW vi

In the heat capacity measurement, we wish to measure the temperature of the cell as a function of time. xt2\_mx\_apr09.vi records the amplified germanium resistor voltage (usually on channel 1) and a reference pulse (usually on channel zero). The reference pulses mark the times at which one expects to see steps in temperature.

- (Figure 10-1). Rather than simply sampling the A/D converter at fixed intervals, this program samples

both channels continuously at 50 kS/s and averages blocks of data at a rate determined by control #1. For example, if the SCAN RATE is set to 10 S/s, the program averages approximately 5000 samples every 100 msec.

- (Figure 10-2). Control #2 sets the time interval at which the display is cleared and data written to file (if the SAVE? switch is set to Yes).
- (Figure 10-3). The SAVE? switch MUST be switched to Yes BEFORE running the vi if you want to save data.
- (Figure 10-4). Use this STOP button to end execution of the program.
- (Figure 10-5). Indicators #5 give the current values of V0, V1 and time since the program started.
- (Figure 10-6). Graph of V0 as a function of time.
- (Figure 10-7). Graph of V1 as a function of time.

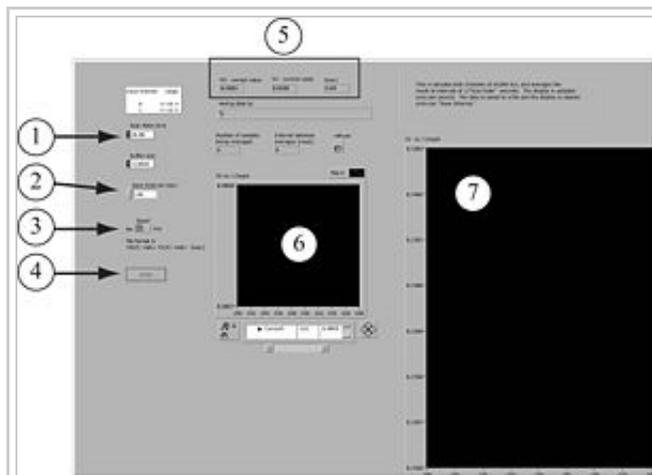


Figure 10. LabVIEW xt2\_mx\_apr09.vi screen shot (partial)

## Matlab Code

Matlab enthusiasts can use a script called XYt\_triggered.m to collect data from the NI-PCI-6014. See the C:\students directory on the laboratory SFHe computer or the appendix below. To run the script, change directory to C:\students and at the Matlab prompt type

```
>>XYt_triggered()
```

As of August 2011, this is beta software and still lacks averaging.

## Germanium resistor calibration

The thermometer mounted on the cell is a germanium resistor. Calibrate it against the official temperature scale based on the equilibrium vapor pressure of  $^4\text{He}$ . Make sure that there is sufficient exchange gas in the vacuum can so that the bath and cell are at the same temperature. This will require saturating the activated charcoal in the cryopump (see next section). Note that the resistance measured for a given temperature may depend on how much power is dissipated in the thermometer for the measurement. Find an appropriate current for the measurement and stick with this current. (Why does the resistance of a germanium or carbon resistor increase with decreasing temperature while a metal film resistor remains constant?). A four-probe resistance measurement is made. You can improve your precision by measuring a set of points and fitting to an appropriate curve such as that proposed by Clement and Quinell (see White). A better fit may be found using a high order polynomial in T, including a  $1/T$  term. Germanium thermometers are fairly stable and maintain their calibration after cycling to room temperature, so you can use your calibration for the remainder of the experiment. *The calibration should only be done when pumping the temperature of the bath down. When helium warms it stratifies in temperature and a large thermal gradient between the bottom and the top surface can develop; the vapor pressure will thus characterize only the helium at the surface.*

## Pumping the vacuum can

A 3/8-inch stainless steel tube connects the vacuum can to the gas-handling manifold, which in turn is

connected to the pump cart. When helium is introduced as an exchange gas, some of the atoms are in the gas phase and some of them condense to form a film on the container walls. As the gas is pumped away, it is replenished by evaporation from the film so evacuation may be slow.

The "workhorse" high vacuum pumping system in the laboratory is a pump cart, which consists of an oil diffusion pump (shown in Fig. 3b) and a backing or roughing pump. The pump cart has a liquid nitrogen cooled cold trap above the diffusion pump for pumping on condensable vapors such as water vapor, which are not efficiently pumped by a backing pump. Vapor diffusion pumps achieve vacuums of order  $10^{-6}$  torr, but only work below about 0.1 torr and must not be exposed to one atmosphere pressure. Roughing pumps achieve ultimate pressures of  $10^{-3}$  torr and can pump on one atmosphere pressure. The procedure to pump an experimental volume is to first use the roughing pump in conjunction with the valves (so that pumping is via the bypass tube) to pump the volume down to about 0.1 torr. Then switch over to the diffusion pump which is pumped-on by the backing pump, with the bypass closed.

Even though the diffusion pump is fast, pumping is through a small diameter tube, which constricts the flow. (How does the gas flow conductance depend on the diameter and length of the pump tube? What is the effective pump speed at the vacuum can? See for example, Dushman.) Since initial pump speeds depend on the pressure squared, evacuation is first fast and then slows down. To properly evacuate the vacuum can (isolate the cell) in this way requires of order 24 hours (too long). To solve this problem we have built a cryopump into the vacuum can so that the pump tube flow impedance is eliminated. Thus in practice, you will not need to use the diffusion pump in this experiment.

The cryopump consists of several pellets of activated charcoal epoxied to a copper surface. Activated charcoal has a surface area of several hundred square meters per  $\text{cm}^3$ . At 4 K or lower a monolayer of helium is strongly adsorbed. A considerable amount of helium can thus be pumped by the charcoal surface before it is saturated. When heated to 30-40 K, the helium is desorbed and thus provides an exchange gas. The copper surface, isolated from the helium bath, is connected to the bath by a small copper wire, so that it will cool down and pump when the heater is turned off. It is also equipped with a heater and Si diode thermometer for monitoring the temperature. You can heat the cryopump, using the Kepco power supply. The diode is forward biased with 10 microamps and you can monitor the voltage to determine the temperature from a provided calibration. Positioning this cryopump inside of the vacuum can reduces the pumping time to several minutes.

When you initially calibrate your thermometer you will have to saturate the charcoal since heating the charcoal to provide an exchange gas also heats the cell. After calibration, pump away most of the gas with the roughing pump (also heating the charcoal). Then make sure that you have enough gas for thermal contact, but not so much that the charcoal will be saturated. This is of order of several  $\text{cm}^3$  of helium gas at one atmosphere, as stated earlier. The amount of gas that should be put into the vacuum can is critical for proper operation of the sorption pump. Too much and the sorption pump can not absorb it all and there will be a thermal coupling to the

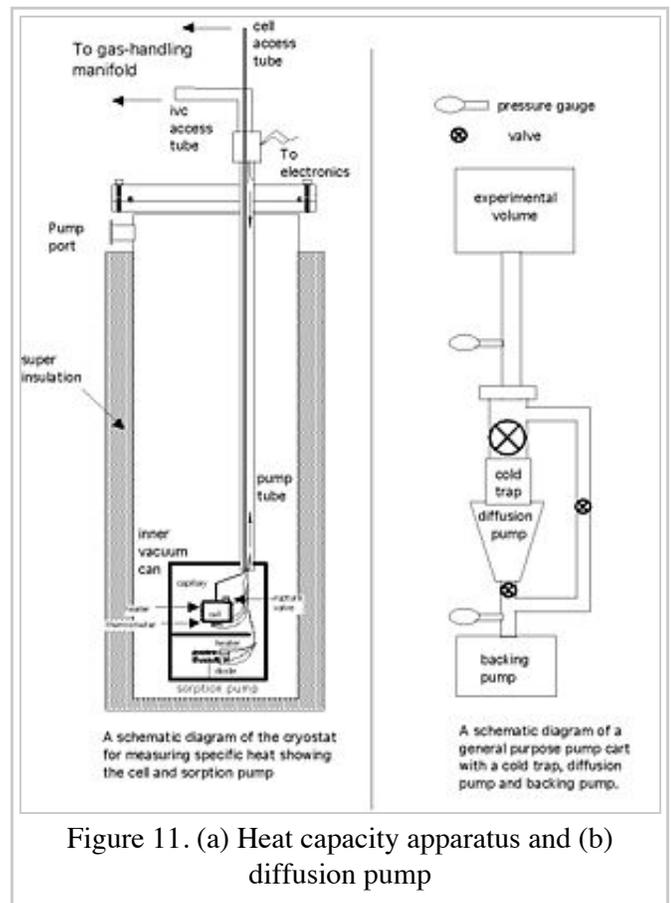


Figure 11. (a) Heat capacity apparatus and (b) diffusion pump

cell; too little and the cell does not get cold enough to span the range of the experiment. It has been found that you should condense gas into the vacuum can from the volume between valves  $V_A$ ,  $V_B$  and  $V_D$ . Helium at a pressure of 10 inches Hg should be adequate.

The optimal procedure for admitting exchange gas for heat capacity measurement is as follows: When you begin lab, the cell should be at liquid nitrogen temperature. The staff will have used the diffusion pump to evacuate the cell and the inner vacuum can while at room temperature, and precooled the cryostat with liquid nitrogen. The cell cools by radiation to 77 K. Your first job is to remove the liquid nitrogen. Next add exchange gas and then transfer helium. The capacitance liquid helium level monitor reads about 745 pF when empty and 765 pF when full. The helium exchange gas, which you measure out between  $V_A$  and  $V_B$  will initially expand into the bellows, which connects the pump cart to the apparatus. The bellows should be evacuated first to preserve the purity of the helium. Opening  $V_F$  at this point will allow some fraction of the gas to enter the vacuum can, but none will condense. Leave  $V_F$  open during helium transfer. As the vacuum can cools to 4.2 K, the pressure in the bellows will decrease as helium is condensed onto the walls of the can and is pumped into the sorption pump. A thermocouple gauge on the pump cart, "TC1", monitors the pressure in the bellows. After transfer,  $V_F$  should be closed and the sorption pump heater turned on. Heat the pump until its temperature reaches about 30K. A rough calibration is given in the bench notes. This causes the exchange gas to come out of the pump but keeps it below  $V_F$ . When the cell temperature stabilizes, turn off the sorption pump heater, and pump the bath below the lambda point to the lowest temperature of interest. Remember to pump slowly for efficiency. Turn the sorption pump heater back on; the cell should approach the bath temperature. If helium heat capacity is to be measured rather than just the addendum, open  $V_E$  and close it again when the desired amount of helium has condensed. Turn off the sorption pump heater when the cell temperature stabilizes. The cell will then cool quickly to the bath temperature, since heat from the sorption pump is no longer affecting its temperature.

For measurement of the heat capacity of He you should fill no more than about 75% of the volume of the cell. This ensures that superfluid helium will not fill the capillary. If it does so, below the lambda point this will introduce a stronger than desired thermal conduction path from the cell to the bath. To pace yourself, allow a minimum of one lab period to calibrate the germanium resistor, one lab period to measure the addendum heat capacity, and two lab periods to measure helium heat capacity.

## Shutdown Procedure

- Shut off the large mechanical vacuum pump used for pumping the helium bath and vent it, making sure it is isolated from the cryostat. Bring the cryostat back up to atmospheric pressure by backfilling with He gas. Remove the end-cap of the pumping-port Tee. *If the cell contains liquid helium, Valve E MUST BE LEFT OPEN.*
- Turn off all electronic instruments.

## NOTES

1. ↑ Precision Cryogenic Systems model PVS-337 LHe Vapo-Shield Dewar. The so-called superinsulation consists of many layers of aluminized Mylar, each of which serves as a successively colder radiation shield.
2. ↑ Wallace & Tiernan absolute-pressure indicators: 0-50 and 0-800 mm Hg
3. ↑ The ribbon measures .065 inch wide by .003 inch thick and has a resistance of 2.441  $\Omega$ /ft. It is wound "non-inductively" on a phenolic disk.

4. ↑ The volume of the cell is  $1.4 \text{ cm}^3$ . The volume of the cell plus the tubes leading to it from the high-purity helium reservoir is  $7.4 \text{ cm}^3$ . The mass of the cell (largely copper) is 14.8 grams.

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## **Experimental techniques**

F.G. Brickwedde, H. Van Dijk, M. Durieux, J.R. Clement and J.K. Logan, The "1958 He 4 Scale of Temperatures", (NBS Monograph 10, US Govt. Print. Office, Washington DC, 1960). This should be with the Bench Notes (and remain there).

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S. Dushman, Scientific Foundations of Vacuum Technique, 2nd ed., J.M. Lafferty, editor, (John Wiley & Sons, New York, 1962). This is the bible on the subject and will explain everything to you. Relevant to this experiment you can read about how mechanical pumps and manometers work.

P. Horowitz and W. Hill, The Art of Electronics, 2nd ed. (Cambridge University Press, N.Y., 1989). If you're not familiar with differential amplifiers or low-noise measurement techniques, this is a good place to start reading.

## **APPENDIX: Matlab script for data acquisition**

```
% XYt_triggered.m
```

```
% reads two voltages from an NI-6014 PCI card to memory and logs to disk
```

```
% sample at 10,000 Samples/second
```

```
% take 100,000 data points on each channel i.e. 10 seconds of data
```

```
% create an analog input object
```

```
ai=analoginput('nidaq','Dev1');
```

```
% add channels

ch0=addchannel(ai,0);

ch1=addchannel(ai,1);

% set sample rate for both channels

set(ai,'SampleRate', 10000);

% turn on logging to disk

% 'Index' mode writes a new file with an indexed suffix for each trigger

FileName = inputdlg('Enter a filename base.','User filename entry dialog');

set(ai,'LoggingMode','Disk&Memory');

set(ai,'LogToDiskMode','Index');

set(ai,'LogFileName',FileName{1});

% set trigger type -- 'Immediate' trigger begins acquisition after start(ai)

% 'Software' uses software-configured channel, condition (slope...) and

% value (level in Volts...)

set(ai,'TriggerType','Software');

set(ai,'TriggerChannel',ch0);

set(ai,'TriggerCondition','Rising');

set(ai,'TriggerConditionValue',0.02);

% set number of samples

NumberSamples = 100000;

set(ai,'SamplesPerTrigger',NumberSamples);

% initialize variables used in loop and open blank figure window

button = ;
```

```
i = 1;

figure();

% start timer

tic;

while(i > 0);

start(ai);

TimeAtStart = toc;

wait(ai,111);

[data,time]=getdata(ai,NumberSamples);

plot(time,data)

stop(ai);

TimeAtStop = toc;

DeltaT = TimeAtStop - TimeAtStart;

button = questdlg('Take another data set?','User run choice dialog');

switch button;

case 'Yes';

i=1;

case 'No';

i=0;

case 'Cancel';

i=0;

case ;

i=0;

end;
```

end;

% clean up for next data run

delete(ai);

clear('ai');

clear('ch0');

clear('ch1');

% to read .daq files, use >>[data2,time2] = daqread('FileName001.daq');

% if script is interrupted, use >>daqreset

## Bench Notes

- Liquid Helium: Pressure (mTorr) vs. Temperature (K)  
([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/pt.txt](http://www.fas.harvard.edu/~phys191r/Bench_Notes/pt.txt))
- The 1958 Helium-4 Scale of Temperatures (P vs. T for lHe4)  
([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/HeScale.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/HeScale.pdf))
- Liquid Helium Transfer Video (Ron Walsworth, 2007)  
(<http://stream.fas.harvard.edu/ramgen/permanent/physics190r/LiquidHeliumTransfer.rm>)
- Appendix 4: How to Transfer Liquid Helium ([http://www.fas.harvard.edu/~phys191r/pdf/ap4\\_09.pdf](http://www.fas.harvard.edu/~phys191r/pdf/ap4_09.pdf))
- Properties of superfluid liquid helium (VIDEO: Michigan State University, 1963)  
([http://www.youtube.com/view\\_play\\_list?p=442F47F12D99C4D2&annotation\\_id=annotation\\_121562&feature=iv](http://www.youtube.com/view_play_list?p=442F47F12D99C4D2&annotation_id=annotation_121562&feature=iv))
- Dell Optiplex 980 Technical Guide ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/optiplex-980-tech-guide.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/optiplex-980-tech-guide.pdf))
- 
- **Helium Transfer Quick Checklist**
- 1. Remove liquid nitrogen
- 2. Remove liquid nitrogen residue
- 3. Measure level in storage dewar
- 4. Precool transfer tube
- 5. Transfer helium into cryostat
- 6. Remeasure level in storage dewar
- 

## Second Sound

- Kepco BOP 50-2M Amplifier  
([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/Kepco\\_bop100W.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/Kepco_bop100W.pdf))
- Liquid Helium Level Monitor ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/AmMag134.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/AmMag134.pdf))
- Cryostat Schematic and Notes ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/Notes.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/Notes.pdf))
- PAR 113 Preamplifier ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/Preamp.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/Preamp.pdf))

- HP 8013B Pulse Generator ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/hp8013b.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/hp8013b.pdf))
- HP 8013A Specifications from 1972 catalog, page 304 ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/HP-Catalog-1972-p304.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/HP-Catalog-1972-p304.pdf))

## Heat Capacity

- *Manuals*
- Tektronix 4020 Multimeter Specification Sheet ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/tek4020.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/tek4020.pdf))
- Tektronix 4020 Multimeter Operator's Manual ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/tek4020\\_op.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/tek4020_op.pdf))
- Germanium Resistor Data Sheet ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/GeRes.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/GeRes.pdf))
- National Instruments PCI-6014 ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/sf\\_6014.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/sf_6014.pdf))
- Model 177 Microvolt DMM ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/Keithley177.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/Keithley177.pdf))

## Calibrations

- Cryopump Diode Calibration ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/cryopump.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/cryopump.pdf))
- Wallace and Tiernan Pressure Calibration ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/wt.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/wt.pdf))

## Principle of Operation

- Thermometry Info ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/thermometry.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/thermometry.pdf))
- Sorption Pumping Info ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/Sorption.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/Sorption.pdf))

## Schematics

- Heat Capacity Amplifier (AMP/DIRECT switch) ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/heat\\_cap\\_amp3.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/heat_cap_amp3.pdf))
- Heat Capacity Pulser Schematic ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/E1/heat\\_cap\\_pulser.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/E1/heat_cap_pulser.pdf))

## Photos



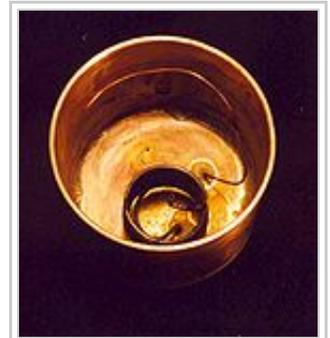
Insert - before relocating capillary



Cell Assembly  
(lowered ~4cm)



Cryopump (top) with resistors and diode

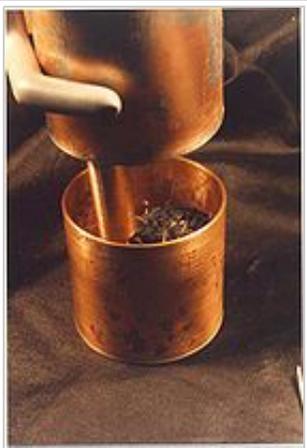


Cryopump can,  
showing pump stem  
and thermal link to bath

Retrieved from "[https://coursewikis.fas.harvard.edu/phys191r/E-1\\_Properties\\_of\\_Superfluid\\_Helium](https://coursewikis.fas.harvard.edu/phys191r/E-1_Properties_of_Superfluid_Helium)"

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Cryopump assembly