Creation and Detection of Low Temperature Helium Atom Beams
and Suspension of Superfluid Helium for the Study of
Bose-Einstein Condensation in Superfluid Helium

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Abstract

We have demonstrated a technique for creating a freestanding layer of superfluid. This has also allowed us to indirectly measure the contact angle of superfluid helium on a cesium-coated surface. Our measurements indicate that surface roughness has a very large effect on the value of the contact angle. We have constructed titanium bolometers and used these bolometers to detect helium atom beams in an experimental cell maintained at 290 mK. Helium atom beams were created by sending electrical heating pulses through thin chromium films. It was found that for input pulse powers of less than 2.5 mW the helium atom beams had a very narrow velocity distribution. The beams created with this input pulse power can be used to study processes that occur when helium atom beams impinge upon the free surface of a suspended layer of superfluid helium and atoms that are emitted from the other side of the superfluid layer are detected. We also found that for high input pulse powers helium atom beams with more than one peak in the time of flight spectrum are observed. The data observed under these conditions may provide insight into the way helium atoms evaporate from thin superfluid films.
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1. Introduction

1.1. Theory

When liquid helium is cooled below 2.17 K it undergoes a transition from a normal liquid to a superfluid. It has long been believed\(^1\) that this transition is associated with Bose-Einstein Condensation. For a system of weakly interacting particles, Bose condensation is defined as a macroscopically large number of particles occupying the same single particle quantum state. The condensate fraction, \(n_o\), denotes the fraction of particles in the ground state. For a system made of strongly interacting particles, such as liquid \(^4\)He at low temperatures, the concept of a condensate fraction can be extended to be described by the one particle density matrix,

\[
\rho_1(\vec{r}, \vec{r}') = N \int \Phi_N^* (\vec{r}_1, \ldots, \vec{r}_N) \Phi_N (\vec{r}'_1, \ldots, \vec{r}'_N) d\vec{r}'_2 \ldots d\vec{r}'_N \quad (1.1)
\]

Where \(\Phi_N\) is the N body wave function of the system. The condensate fraction is defined as \(n_o\), where

\[
\lim_{|\vec{r}, \vec{r}'| \to \infty} \rho_1(\vec{r}, \vec{r}') = n_o \left(\frac{N}{V}\right) \quad (1.2)
\]

This is consistent with the limit of weakly interacting systems, where as \(T \to 0\), the condensate fraction will approach unity and the one particle density matrix,
\[ \rho_1(\mathbf{r}, \mathbf{r'}) \rightarrow \left( \frac{N}{V} \right) = n_0 \left( \frac{N}{V} \right), \quad (1.3) \]

is independent of \(|\mathbf{r} - \mathbf{r}'|\).

Since weak interactions between the particles deplete the condensate\(^2\), for a strongly interacting system such as superfluid helium, the condensate fraction is expected to be small. Only neutron scattering experiments have thus far been able to make any measurements of the condensate fraction in superfluid helium, and interpretation of these experiments is difficult. One prominent researcher in the field, Prof. Paul Sokol, stated recently that it is clear that a direct observation of the condensate through neutron scattering measurements is unlikely in the foreseeable future.\(^3\) The fact that so little is known about the basic cause of a widely studied phenomenon such as superfluidity provides the motivation for our research.

Our proposed experiment\(^4\) is one in which a low energy helium atom beam impinges on the surface of a freestanding superfluid helium layer, as shown in Figure 1.1.1. Helium atoms emitted from the surface on the opposite side of the superfluid helium layer are detected. In our original proposal it was suggested that, due to the macroscopic population of the condensate, a helium atom impinging upon the lower surface would have a significant probability of coupling to the condensate and then being promptly re-emitted at the surface on the other side of the superfluid layer.\(^4\) Classically, this process is
not possible because it does not conserve energy in the intermediate state, but quantum mechanically it is possible within the constraints of the uncertainty principle, which states that

$$\Delta E \Delta t \leq \hbar,$$  \hspace{1cm} (1.4)

where $\Delta E$ is the energy of the incoming particle relative to the ground state and $\Delta t$ is the transmission time. For $\Delta E = \mu$ we can estimate the transmission time to be a few picoseconds. In the first theoretical analysis of this problem, second order perturbation theory was used to estimate the cross section for such a process. It was found that, in addition to the unusual time dependence expected for this process based on the uncertainty principle, the cross section for the process should depend on the area of the incoming beam to the fourth power. It was also found that for areas larger than about 1 nm$^2$, the simple perturbation theory calculation gave a very large cross section for the condensate process. This indicates that the perturbation theory is no longer valid for larger areas and a full many-body computation of the process is required.

Such a calculation has been made by Arun Setty, in which he calculates the transmission amplitude and time dependence of a process where a low energy $^4$He atom is incident on one side of a slab, couples to the ground state and is then emitted on the other side of the slab.\(^5\) The transition amplitude was found to be of order unity and the transmission time of the order of a few picoseconds, in agreement with the uncertainty principle argument. The calculations were done for a slab thickness of 2 nm and 4 nm. It was also found that,
within the uncertainty of the calculation, the transmission time was independent of slab thickness. This is also in agreement with the predictions of reference 4. The prediction of the area scaling of the cross section for the process was not tested in this calculation.

In addition to the condensate-mediated process, we also expect to be able to observe processes associated with the creation of excitations in the superfluid. It has been found that an atom incident on a free surface of superfluid helium will be absorbed and create an excitation in the superfluid with energy equal to the kinetic energy of the incoming particle plus the magnitude of the chemical potential of the liquid.\(^6\) It has also been found that when an excitation in the superfluid with energy greater than the chemical potential reaches the surface it can cause evaporation of a \(^4\)He atom.\(^6\) These processes are called quantum absorption and quantum evaporation, respectively. The two most significant excitations, phonons and rotons, are indicated in the excitation spectrum shown in Figure 1.1.2. Although the separate processes of an incident atom creating an excitation in the superfluid and an excitation in the superfluid quantum evaporating an atom have been seen experimentally, an experiment to see a back-to-back quantum absorption, quantum evaporation process mediated by ballistic rotons has never been done due to the necessity of a slab of superfluid with two parallel free surfaces. Experiments that demonstrate the suspension of such a superfluid slab\(^7\) will be discussed in Chapter 2.
Figure 1.1.1. Schematic of the proposed experiment to detect the condensate in superfluid helium. Low energy helium atoms travel from the source and impinge upon the lower surface of the liquid helium. Atoms which are emitted from the upper surface are detected and the time of flight is measured.

Figure 1.1.2. Excitation spectrum of superfluid helium.
Helium atom beams consisting of a large number of helium atoms can be created with translational energies ranging from 1.5 K to 3 K.\textsuperscript{8} This is the region of interest and is marked as a shaded region in Figure 1.1.2. Since the chemical potential of superfluid helium is -7.15 K,\textsuperscript{9} a helium atom with a translational energy in this range will create an excitation with an energy ranging from 8.65 to 10.15 K. It has been shown that a phonon with an energy lower than 10 K will decay into a number of phonons of lower energy after traveling distances that are small compared to the thickness of the superfluid layer.\textsuperscript{6,10} These lower energy phonons will not have sufficient energy to produce quantum evaporation from inside the superfluid layer. Thus an incoming atom with energy in the range of interest will not evaporate an atom on the other side of the superfluid layer if a phonon is created upon condensation. As is evident from Figure 1.1.2, it is also possible to create a roton from quantum condensation. Unlike phonons, rotons do not decay into lower energy excitations. At a temperature of 100 mK, the roton mean free path is about 1 cm, which is longer than the thickness of the superfluid helium layer.\textsuperscript{6} This will allow a roton that is created at one side of the slab to travel through the superfluid and cause the quantum evaporation of a $^4$He atom from the opposite side of the slab. This will be referred to as the ballistic roton process. The group velocity of rotons varies from $v_g=0$ at the roton minimum to a maximum value of $v_g=240 \text{ m/s}$ as the roton energy is increased. Using the maximum group velocity of a roton in the superfluid of 240 m/s and a slab thickness of 2 mm, we can estimate that a roton will cross the slab in no less than 8 $\mu$s.
1.2. Experimental Overview

In order to perform this experiment, there are three key requirements. First, we need a suspended slab of superfluid helium. Second, we need a low energy helium atom beam source with a narrow energy distribution. Finally, we require a sensitive helium atom detector with a time resolution sufficient to distinguish a picosecond from a 10 µs process. In addition to these three elements, the experiment must be carried out in a chamber containing superfluid helium at 100 mK.

The one element that had not been previously demonstrated when we started this project was the suspension of superfluid helium. Since that time levitation of droplets of liquid helium has been demonstrated using a laser\textsuperscript{11} and using a magnetic field.\textsuperscript{12} In the laser levitation experiment, it was found that the maximum droplet size was about 20 µm. Droplet sizes in this range would not be useful because the transmission time through a droplet for the ballistic roton process would be much less than the time resolution available for low temperature detectors. Droplets 2 cm in diameter have been levitated using a gradient-coil superconducting magnet built by Oxford Instruments. Droplets in this size range would be suitable for our experiment but require such high magnetic fields that it would be impossible to use a bolometer anywhere near the droplet. Superconducting bolometers would not work at all and semiconductor bolometers would be difficult to use. Semiconductor bolometers are not appropriate for our experiment in any case since they generally have time constants of the order of milliseconds rather than microseconds.\textsuperscript{13}
We use a novel technique that exploits the recently discovered fact\textsuperscript{14} that superfluid helium does not wet cesium-coated surfaces. The idea is that if a fluid enters an orifice whose surface it does not wet, then a meniscus will form which can suspend a column of fluid above it in the presence of gravity. We were able to demonstrate this technique by suspending 2 mm of superfluid helium above a 70 \( \mu \text{m} \) diameter cesium-coated platinum orifice at 1.2 K.\textsuperscript{7} Chapter 2 is devoted to a description of this experiment.

In order to perform the condensate transmission experiment a dilution refrigerator, capable of cooling superfluid helium down to 100 mK, is required. We purchased a CF-25 dilution refrigerator insert from Janis Research Co, Inc. In addition to the insert, a dewar and a sealed mechanical pump were also purchased from Janis. I then designed and constructed a frame for the dewar and refrigerator as well as a gas handling system for operation of the cryostat. A description of the dilution refrigerator system and a general cool down procedure are given in Chapter 3.

After demonstrating the ability to suspend a slab of superfluid helium, we developed the techniques necessary to create monochromatic beams of helium atoms and to detect them. It was determined that superconducting bolometers were the best type of detector to use for such an experiment due to the low noise obtainable with such detectors at low temperatures. Additionally, superconducting bolometers with time constants of less than 1 \( \mu \text{s} \) had been demonstrated.\textsuperscript{15} These previously demonstrated superconducting bolometers were made from thin films of zinc coated on sapphire substrates. We began
by making similar zinc films by thermal evaporation. These films had a superconducting transition at 0.7 K, which is slightly lower than the bulk transition of 0.85 K. However, our operating temperature is expected to be 0.3 K, so the only way to use these films as detectors is to apply a magnetic field parallel to the film to lower the superconducting transition temperature. Creating a field in this direction at the correct order of magnitude to lower the transition to 0.3 K would be difficult and expensive, so this was abandoned and a new type of superconducting film was found.

Titanium has a bulk superconducting transition of 0.39 K, so we attempted to construct bolometers from thin films of titanium. We made titanium films both by thermal evaporation and by sputtering. Only the sputtered films exhibited a superconducting transition above 43 mK. Their transition was at 0.44 K. This is close enough to the cell operating temperature to be used without applying an external magnetic field to lower the transition temperature. The bolometers and their operation are described in detail in Chapter 4.

The last key element needed for the experiment is a low energy helium atom beam source. The best source for such a beam in an experiment with superfluid helium is to use a thin normal metal film that is covered with a thin film of superfluid helium. If a current pulse is sent through the metal film, it heats up to a temperature at which the superfluid film has a high vapor pressure, thus causing the evaporation of a large number of helium atoms. If the pulsed beam is created at the right power levels and times, a very cold, low energy atom beam can be created. For our experiments we used three different types of
beam sources. One was a thin film of chromium evaporated onto a 1 mm diameter sapphire substrate. Another was one of the 2.5 mm diameter sapphire substrates with a titanium film evaporated onto it. (This film did not superconduct.) A third source that was used was a commercial ruthenium oxide thermometer. The helium atom beam experiments are described in Chapter 5. Chapter 6 contains conclusions and designs for future experiments.

1  F. London, Nature 141, 642 (1938)
8  N. Mulders, private communication
2. **Suspension of Superfluid Helium Using Cesium-Coated Surfaces**

2.1. **Background**

Before 1991, superfluid helium was believed to be a universal wetting agent. This means that an isothermal cell that contains superfluid helium will have a thin film of superfluid covering all surfaces in the cell. The films are typically 30 nm thick, depending on the nature of the substrate. This is thick enough to allow the superfluid to flow along the film. The superfluid will flow until thermodynamic equilibrium is reached. Since the lowest energy configuration is one in which most of the liquid is at the bottom of the cell, it would be impossible to suspend helium for a significant amount of time without somehow separating the bulk liquid from the thin superfluid film. If helium wets all surfaces, the only way to do this is to levitate a droplet so that none of the bulk helium can touch another surface.

In 1991 it was predicted that superfluid helium would not wet cesium surfaces.¹ Later that year the first experimental evidence for the nonwetting of superfluid helium on cesium-coated surfaces was published.² In this experiment, a ring of cesium was coated onto the inside of a glass tube. Helium was added to the tube so that a superfluid film would cover all surfaces. It was demonstrated that there was no superfluid film on the cesium-coated surface, which indicated that the superfluid did not wet the surface. However, a measurement of the contact angle, which must be nonzero if the liquid does
not wet the substrate, was not made. Later experiments, discussed in a review article, demonstrated nonwetting of superfluid helium on cesium by other techniques, all of which involved simply showing that a thick superfluid film did not exist on a cesium surface. In one experiment it was demonstrated that third sound was not transmitted across a cesium surface under conditions such that a superfluid film would be expected to cover all surfaces. Third sound was blocked only when the helium was below saturated vapor pressure, which means that the presence of a much thicker film caused the superfluid to wet the cesium surface. Similarly, Rutledge and Taborek used a quartz microbalance to measure the superfluid film thickness on a cesium-coated surface and found that below saturated vapor pressure there was no helium film. In later experiments these workers were able to make cesium surfaces that were not wet by superfluid helium at saturated vapor pressure. They were also able to measure a wetting transition temperature of approximately 2 K. It was clear from this research that it was very difficult to make cesium surfaces that superfluid helium did not wet, but that it should be possible for us to reproduce this behavior.

2.2. Using a Nonwetting Surface To Suspend a Liquid

We consider a nonwetting fluid in a hole with cylindrical symmetry as shown in Figure 2.2.1. Mechanical stability at the surface of the resulting meniscus is assured by balancing the force due to the pressure on an element of surface with the force on the element due to the surface tension giving, in general, the Laplace equation.
\[ P_l - P_g = \sigma_{lv} \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \]  

(2.1)

Here \( R_1 \) and \( R_2 \) are the principal radii of curvature of the surface element, \( P_l \) and \( P_g \) are the liquid and gas pressures and \( \sigma_{lv} \) is the surface tension (or energy per unit area) of the liquid vapor surface. In the configurations of Figure 2.2.1 \( R_1 = R_2 = R \). The liquid pressure \( P_l \) is given by

\[ P_l = \rho gh , \]  

(2.2)

where \( \rho \) is the liquid density, \( h \) is the depth of the fluid above the surface element, and \( g \) is the acceleration due to gravity. In the present application \( P_g \), the gas pressure, is the saturated vapor pressure of helium at 1.2 K. The solution to (2.1) for the surface curvature is subject to the boundary condition that the contact angle is fixed at the value \( \theta \) determined by the liquid-substrate interaction through the Young condition

\[ \sigma_{sv} - \sigma_{sl} - \sigma_{lv} \cos \theta = 0 \]  

(2.3)

When we began our experiments to suspend superfluid helium using a cesium-coated orifice, the contact angle of superfluid helium on a cesium-coated surface had not been measured, but it was clear from existing measurements of the wetting transition that it
was likely to depend on the particular cesium surface used. The first theoretical estimates of the contact angle\textsuperscript{1} gave values somewhat larger than $\pi/2$, whereas estimates\textsuperscript{10} based on the experimentally measured values of the temperature of the wetting transition gave much smaller values. The qualitative behavior of the fluid in a hole such as that sketched in Figure 2.2.1 depends on whether the contact angle is greater than or less than $\pi/2$. If $\theta > \pi/2$ then, for a low enough depth $h$ of the fluid, a meniscus will form at the top of the hole, as sketched in Figure 2.2.1(a). For this same $\theta > \pi/2$ increasing the depth $h$ of the fluid will lead to the situation shown in Figure 2.2.1(b) in which a stable meniscus has formed at the bottom of the hole. On the other hand if $\theta < \pi/2$, then the meniscus cannot form at the top of the hole but could form at the bottom of the hole as shown in Figure 2.2.1(c).
Figure 2.2.1. (a) Schematic cross section drawing of a fluid suspended by its meniscus across a cylindrical hole in a material whose surface the fluid does not wet and for which the contact angle $\theta > \pi/2$. (b) Second stable configuration for the case that $\theta > \pi/2$. (c) Stable configuration for the case that $\theta < \pi/2$.

To get quantitative estimates of the maximum supportable depth of helium fluid in the two cases we will suppose that the pressure is uniform over the surface. Near the critical depth $h_c$ below which the meniscus is stable, this condition is satisfied if the radius $r$ of the hole satisfies $r \ll l$ where the length $l$, defined as

$$l \equiv \sqrt{\frac{2\sigma}{\rho g}}$$  \hspace{1cm} (2.4)
is about 0.10 cm at 1.2 K (using $\rho = 0.145$ g/cm$^3$ and $\sigma_{lv} = 0.342$ dyne/cm). In the case (a) the critical depth $h_c^a$ is given by

$$h_c^a = \left(\frac{l^2}{r}\right)\cos \theta$$  \hspace{1cm} (2.5)

whereas in case (b) the critical depth is

$$h_c^b = \left(\frac{l^2}{r}\right)$$  \hspace{1cm} (2.6)

and in case (c) it is

$$h_c^c = \left(\frac{l^2}{r}\right)\sin \theta$$  \hspace{1cm} (2.7)

In each case the critical depth is given by the configuration which minimizes the radius of curvature of the surface while maintaining the fixed contact angle with some part of the wall. Thus, in case (b) the configuration that has the smallest radius of curvature is one in which the liquid surface is perpendicular to the horizontal surface. The contact angle is greater than 90°, but the liquid-solid interface occurs at a point along the corner that allows the liquid surface to extend directly downward, as shown in the figure. In case (c) the 90° configuration will never satisfy the contact angle restriction, so the smallest radius of curvature is obtained when the surface makes an angle of $\theta$ with the horizontal surface. When these experiments were performed, the contact angle $\theta$ was not known. The estimate of reference 1 was 95° at T=0, whereas the values of $\theta$ as a function of temperature given in reference 10 were substantially smaller and were inferred from the observed wetting temperature as follows: At the wetting transition $\cos \theta = 1$, so by use of
the Young condition (2.3) and the experimentally known values\textsuperscript{12} of $\sigma_i$, one can infer
that, at the wetting temperature, $\sigma_{sv} - \sigma_{sl} = 0.306$ dyne/cm.

Assuming that $\sigma_{sv} - \sigma_{sl}$ is not temperature dependent, one can infer the temperature
dependence of $\theta(T)$ from the experimentally measured\textsuperscript{12} temperature dependence of $\sigma_i$. For example, at 1.2 K this procedure gives 26.7° for the contact angle. We show the
predicted contact angle over the full range of temperatures in Figure 2.2.2 using this
procedure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{contact_angle_plot.png}
\caption{Contact angle as a function of temperature as predicted from data on $\sigma_i$
and the experimentally measured wetting transition temperature as discussed in the text.}
\end{figure}
We may now use these various estimates of $\theta$ to infer predicted critical depths. In doing this, we take account of the fact that the hole used experimentally actually has a conical shape at the bottom as shown in Figure 2.2.1. This requires that we use a different radius $r$ (the radius of the hole at the bottom) in the expressions for $h^b_c$ and $h^c_c$ than in the equation for $h^a_c$ where we use the radius at the top. With top and bottom radii of 35 $\mu$m and 100 $\mu$m respectively we find that if $\theta$ were 95° we would have $h^a_c = 1.2$ mm and $h^b_c = 4.8$ mm. On the other hand if the values of $\theta$ in Figure 2.2.2 are appropriate then we find at $T=1.2$ K that $h^c_c = 2.2$ mm. In the latter case, the predicted values of $h^c_c$ as a function of temperature are shown in Figure 2.2.3.

![Figure 2.2.3. Predicted critical height $h^c_c$ for the case (c) of Figure 2.2.1 using the values for $\theta$ in Figure 2.2.2.](image-url)
2.3. Apparatus

To test the prediction that we can use this technique to suspend superfluid helium, we must perform an experiment using a container with a hole of the appropriate size at the bottom. The container must be sealed in such a way that the superfluid helium cannot escape to a level lower than the hole in the bottom of the container without going through that hole. To verify that the helium is suspended, the level of helium in the container must be measured to an accuracy which is a small fraction of the expected maximum depth. For the hole with which we worked this requires a depth measurement accurate to within 0.1 mm. To guarantee that the helium is superfluid, the temperature must be well below 2 K and to avoid complications due to the thermomechanical effect, the temperature must be uniform throughout the container.

A drawing of the apparatus, which meets these requirements, is shown in Figure 2.3.1. It consists of two nested brass cans that are completely sealed except for a stainless steel tube connecting the inner can to a valve at room temperature. The only path between the two cans is through the cesium-coated aperture at the bottom of the inner can. The entire apparatus is housed in a pumped helium bath.
Figure 2.3.1. Cross section of the cryostat used for cesium deposition and superfluid helium suspension. The apparatus is housed in a pumped helium bath and consists of nested brass cans sealed to the flange at the top with indium o-rings. Cesium is deposited from below with the cryostat held at 4 K. After cooling to 1.2 K, helium is introduced from above through the 0.5” diameter tube in the center. (Only the bottom portion of the tube is shown in the diagram.) The two coaxial capacitors shown are used to measure the level of superfluid helium in the upper chamber.

The orifice used was a platinum-iridium (95:5) aperture obtained from Ted Pella, Inc.\textsuperscript{13} These apertures, which are normally used for Scanning Electron Microscopes, have an outside diameter of 3 mm and a thickness of 0.12 mm. A number of 1/32” thick 3/16” diameter brass discs with two edges cut to a width of 0.165”, as shown in Figure 2.3.2, were made. A hole 1/8” in diameter was milled in the center of the aperture mount to a
depth of 0.12 mm. A 1/16” diameter hole was then drilled through the center of the aperture mount. The aperture was then inserted into the milled hole and bonded using Stycast 1266 epoxy. In order to attach the mount to the bottom of the inner can, a hole 1/8” in diameter was drilled in the bottom of the inner can. From the top of the can a 3/16” diameter hole was milled to a depth of 1/32”. The inner can was heated to a temperature of 200 °C on a hot plate and the mount, with the aperture already epoxied into place, was soldered into the milled hole using a low temperature Indium solder. In this way, the aperture was completely sealed to the inner can and the top of the aperture was at the same level as the bottom of the can, within 0.005 inch.

![Diagram of mount for platinum orifice.](image)

*Figure 2.3.2. Diagram of mount for platinum orifice.*

The level of superfluid helium in the upper can is measured using the coaxial capacitor shown in Figure 2.3.1. A second coaxial capacitor is kept above the inner can to form a stable reference capacitor at the same temperature as the first. A detailed drawing of one of the capacitors is shown in Figure 2.3.3. A capacitance bridge is then formed by comparing the impedance of the two coaxial capacitors. A diagram of the capacitance
bridge is given in Figure 2.3.4. A ratio transformer is used as the balancing arm of the bridge, which is driven by a 5 kHz oscillator through an isolation transformer. The outer shields of the coaxial capacitors and cables leading to room temperature are tied to ground and a lock-in amplifier measures the voltage at a point between the two capacitors with respect to ground. When the voltage is zero, the capacitance measured should be independent of the capacitance of the cables that connect the capacitors to the bridge, since the inner and outer conductors are at the same voltage. The ratio of the transformer windings needed to balance the bridge gives the ratio of the capacitance of the two capacitors in the cryostat. Bridges similar to this have been used successfully to measure capacitance with a resolution of better than 1 part in 10^6.

![Diagram of the brass capacitor](image)

*Figure 2.3.3. Detailed drawing of one of the brass capacitors used to measure the level of helium in the cryostat. The inner and outer conductors are electrically isolated from and attached to the outer shield with 1/64” sapphire balls. These conductors are connected to coaxial cables with small coaxial connectors with the outer shields of the cables soldered directly into the outside can of the capacitor.*
Figure 2.3.4. Schematic of the capacitance bridge used to measure the level of helium in the upper can. The ratio transformer is adjusted to null the signal on D, a lock-in amplifier that measures the voltage with respect to the grounded shields at a position between the two capacitors. The capacitance of the measurement capacitor is given by $C_x = C_r [(1/R) - 1]$, where $R$ is the reading from the ratio transformer.

### 2.4. Experimental Procedures and Results

We calibrated the apparatus by measuring the level of known amounts of superfluid helium by replacing the hole at the bottom of the inner can in Figure 2.3.1 with a solid piece of brass that was soldered into place. The apparatus was then cooled to 1.2 K and helium gas was introduced in known amounts. Since the volume of the chamber had been measured, each known amount of gas corresponded to a known level of liquid. The capacitance bridge was balanced and the ratio was read from the transformer. This was repeated until the level no longer changed, indicating that the liquid helium had reached...
the top of the capacitor. The results of the calibration are shown in Figure 2.4.1, where the expected linear capacitance change with liquid level is observed. To estimate the uncertainty in the height measurement, we fit the data to a straight line. The standard deviation of the straight line from the data as calculated from the fit was 0.05 mm. The first two points were not included in the fit because they have a very different slope than the rest of the data. This difference in slope was reproducible and is probably due to the effect of fringing fields at the bottom of the coaxial capacitor. Taking the fit line as a determination of the accuracy of the measurement we estimate that the measurement of the helium level is accurate to less than 0.1 mm. This is equivalent to accuracy in the capacitance measurement of 1 part in $10^4$. 
After this calibration of the level measurement, the brass plate was removed from the bottom of the inner can and a platinum aperture of thickness 30 µm containing a 70 µm diameter aperture was epoxied in its place. (Some preliminary experiments using a gold foil were reported earlier.\textsuperscript{15}) The inner can was then sealed to the cryostat. Two commercially obtained cesium evaporators\textsuperscript{16} were set up below and on either side of the hole as shown in Figure 2.3.1. The outer can was then sealed to the cryostat around the cesium sources.

\textit{Figure 2.4.1. Calibration of the capacitance level measurement device. For each point a known amount of helium is introduced into the sealed inner can of Figure 2.3.1 and the capacitance ratio change is measured. Theory predicts that the capacitance will depend linearly on the helium level.}
Before coating the hole with cesium using these evaporators, we first performed an experiment with the uncoated hole in place to verify that superfluid helium could be detected flowing through the hole when it was not coated with cesium. The cryostat was cooled to 1.2 K and purified helium gas was introduced into the upper can through a regulating valve at room temperature. The helium level (Figure 2.4.3) increased very quickly as the helium gas condensed on the walls of the tube and flowed into the upper chamber, filling the lower capacitor. When the regulating valve was closed the slowly decreased linearly in time. The velocity through the hole was independent of height, as is expected for superfluid helium moving through a small orifice. We estimate the velocity as 0.5 cm/s from the data in Figure 2.4.3. This is consistent with estimated critical flow velocities through this hole as discussed in the next section. The helium was then pumped out of the cryostat and it was warmed up to room temperature. Pumping out the helium resulted in the dramatic drop in level which is evident at the end of the run in Figure 2.4.3. (We pumped out the helium in this way at the end of each run in order to confirm that the measured level reaches zero again after the helium is pumped out, so that one sees similar drops in the level at the end of the run in each of the following figures.)

To perform the experiments with the cesium coated hole, the cryostat was next cooled to 4 K, and an approximately 1 µm thick layer of cesium was deposited into the hole. The amount of cesium deposited was estimated from data supplied by the manufacturer.
regarding the rate of cesium evaporation for the current of 7 A that we used, and assuming the density of the coated film to be equal to that of bulk cesium (1.997 g/cm$^3$). The initial emissions from the evaporator were not blocked by movable shutters such as those used by other workers,$^5$ but the cesium dispensers contained a getter alloy which absorbs contaminants \textit{in situ}. Our evaporation method is similar to that used in reference 4, in which non-wetting was observed only below saturated vapor pressure, but this was later attributed to surface roughness.$^6$ On the basis of this history it seems quite possible that our methods can lead to non-wetting surfaces. The apparently successful suspension experiment described below suggests that a non-wetting surface was achieved.

To examine the effect of surface roughness, we wrote a simple code to simulate the ballistic deposition of cesium on corners like the ones encountered at the bottom of the hole. Using angles similar to those encountered in the experiment, ignoring diffusion of the cesium which may occur after sticking, and assuming unit sticking coefficient we obtain structures such as those shown in Figure 2.4.2 for a single source 1 cm away from the hole. Formation of columns as well as some enhancement of the thickness near the corners is evident. Though we cannot rule out some effects of this sort of uneven deposition on the experimental results, we note that the anticipated effects will be smallest in the case of suspension of the type shown in Figure 2.2.1(c) which we favor for the interpretation of these experiments.
Figure 2.4.2 Representative results of a simulation of the ballistic cesium deposition process.

After the cesium was deposited, the cryostat was again cooled to 1.2 K, and purified helium gas was introduced through the regulating valve in an amount corresponding to 4 mm of liquid. The helium level was observed to fall linearly with time (Figure 2.4.4) with the same slope as in the run without cesium. This may imply that the amount of helium introduced in this run was more than the critical height discussed in section 2. The helium was pumped out and the cryostat warmed to above 4 K. At this point the cryostat was allowed to warm up close to room temperature before the next runs were performed.
Figure 2.4.3. Superfluid helium level in the upper can of Figure 2 as a function of time above a 70 µm diameter platinum orifice when no cesium was present. The results are consistent with previously measured critical velocities in superfluid helium.
Figure 2.4.4. Superfluid helium level as a function of time above the platinum orifice after it has been coated with cesium. In this run an amount of helium corresponding to a fluid level height of 4 mm was introduced. The level drops at a constant velocity, suggesting that the depth was larger than the critical height throughout the run. The stable level at 1.9 mm at the end of the run was not maintained long enough to determine whether or not suspension occurred.

In the next run (Figure 2.4.5), helium gas corresponding to roughly 2 mm of liquid was introduced at 1.2 K. The level was at first observed to fall linearly, but it then rose slightly and leveled off after 2 hours. It appears that the helium began to flow through the hole but then formed a stable interface at a later time. If this interpretation is correct, then introducing even less helium should also lead to a stable level.
Figure 2.4.5. Superfluid helium level as a function of time above the cesium coated platinum orifice. In this run, an amount of helium corresponding to a fluid level height slightly greater than 2 mm was introduced. The helium at first begins to flow through the hole and then stabilizes after 2 hours at a level of about 2 mm.

Finally we report the result of introducing an amount of helium gas corresponding to 1 mm of liquid in Figure 2.4.6. The level was observed to remain constant over the entire 2 hour run. The noise in the signal for this run is larger on this scale, but the variation is less than 0.1 mm in level. Based on the previously observed critical velocity for this hole, a change in level of over 3 times that uncertainty is expected by the end of this run. This clearly demonstrates a constant level of superfluid helium for over two hours under these conditions.
Figure 2.4.6. Superfluid helium level as a function of time above the cesium-coated orifice when the amount of helium introduced corresponded to a depth of 1 mm. The data indicates suspension of 1 mm of superfluid helium for almost 2 hours.

2.5. Discussion

The velocity of 0.5 cm/sec estimated from the slope of the superfluid helium level versus time shown in Figure 2.4.3 is in agreement with previous experimental determinations of the value of the critical velocity for flow through a 70 µm hole. After cesium deposition, a critical velocity can be estimated from the slope of the level during the run shown in Figure 2.4.4. This gives a critical velocity of 0.5 cm/s. However, measurement
of the slope of the level during the first two hours of the run shown in Figure 2.4.5 gives a critical velocity of 0.2 cm/s. It is not unprecedented to see changes in observed critical velocity of up to a factor of 2 for the same orifice in two different cool-downs,\textsuperscript{18} so the observed change in critical velocity after warming the cryostat may have nothing to do with the cesium. However, it is also possible that annealing the cesium substrate changed its wetting characteristics and thus affected the critical velocity through this orifice.

It may be objected that we have only observed a difference in flow rates and that the cesium only slowed the flow rate through the hole until it was too small for our instruments to detect. In the experiment of Figure 2.4.5 however, the data would imply the existence, in this interpretation, of two different flow rates through the same orifice under different pressure heads. On the other hand, in a superfluid, only one critical velocity is expected through a given orifice independent of pressure. There have been experiments in which two very different critical velocities have been observed through the same orifice,\textsuperscript{19,20} but in those cases the anomalous critical velocity was much greater than that which is typically observed. Since our critical velocity values are consistent with those reported\textsuperscript{18}, it is unlikely that a significantly lower critical velocity would be observed in this case. Therefore a more reasonable interpretation is that the fluid is in fact suspended at the later times in this experiment (i.e. that the second velocity is really zero.)
We must also consider the possibility that the superfluid helium in the upper chamber will be heated as its level is lowered due to the fact that only the superfluid fraction can flow freely through the orifice. If this heating were to cause a temperature difference of a few mK between the upper and lower chambers, this could cause a pressure difference due to the thermomechanical effect. This might lead to a suspension of helium having nothing to do with the presence of cesium. If one assumes that the upper chamber and lower chamber are completely thermally isolated, the temperature difference that would develop after two hours in a chamber with 2 mm of liquid flowing out at a rate of 0.2 cm/s is 5 mK, which corresponds to a pressure difference of 2.5 cm. However, the helium in both chambers is in direct contact with brass walls that are both in direct contact with the helium bath on the outside of the cans. Thus the effect of Kapitza resistance on the thermal conductivity from the bath to the helium in both chambers should be the same, while the thermal conductivity of the brass itself would allow only temperature differences of the order of microkelvin. Most important, we did not observe any such suspension in the run without cesium coating after running for six hours. It is therefore unlikely that the suspension observed is due to this type of heating.

It is possible to interpret the data of Figures 2.4.5 and 2.4.6 to obtain an experimental estimate of the contact angle. We may suppose that in the experiment resulting in the data of Figure 2.4.5, the helium level was first above the critical value so that the fluid flowed through the orifice but reached the critical level at $h = 2$ mm when the flow stopped. In Figure 2.4.6 the level was, in this interpretation, always below the critical value.
Which expression for the critical depth to use in interpreting the experiments depends on whether we believe the experimentally inferred values of the contact angle in Figure 2.2.2 or the theoretical estimate of reference 10, which was larger than 90°. In the latter case, the observed critical depth is of about the same order as $h_c^a$ but is much smaller than $h_c^b$. Thus if $\theta$ were larger than 90° our experiment could only be explained if the stable state associated with Figure 2.2.1(b) were not achieved (say because fluctuations pushed the fluid past the stable configuration to the unstable one which would result if more fluid flowed into the hole starting at the state described in Figure 2.2.1(b).) Though we cannot totally rule out this possibility, we think it much more likely that the contact angle always remains less than 90°, as in the experimentally based predictions of Figure 2.2.2. Then we can use the expression (2.7) for $h_c^e$ to infer the contact angle from the measured value of the critical depth,

$$\theta = \sin^{-1}\left(\frac{\rho gh_r^2 r}{2\sigma}\right)$$

and inserting our experimental value of $h_c = 2\text{mm}$ we thus obtain $\theta = 24.5° \pm 1.3°$ which is quite close to the value of 26.7° predicted at 1.2 K in Figure 2.2.2. It would be necessary to repeat this experiment many times in order to obtain an accurate quantitative value for the contact angle. However, we can regard this experiment as providing a rough measurement of the contact angle.

Klier, Stefanyi, and Wyatt made the first published measurements of the contact angle of superfluid helium on a cesium-coated surface. According to their measurements, the
T=0 contact angle is 48°. At 1.2 K, their measurement was 40°. Those values are much greater than the measurements from our experiment and they disagree with the values calculated from the surface tension measurements and the wetting transition temperature shown in Figure 2.2.2. These differences can be explained if their surfaces are smoother than ours, which is expected since their surfaces were created at a temperature of 200 °C, while ours were created at low temperature. However, this does not explain the disagreement with the results of Figure 2.2.2, which were calculated for an ideal surface.

If the results of reference 21 are correct, the quantity $\sigma_{sv} - \sigma_{sl}$ is not independent of temperature, suggesting that there are ripplons at the helium-cesium interface.\(^{22}\)

After these results were published, we attempted to reproduce the suspension in the same apparatus after exposing the cesium-coated orifice to air and then cooling down and coating another 1 µm layer of cesium onto the orifice from below. The results are shown in Figure 2.5.1. When 1.7 mm of liquid is added to the cell, a stable level is observed after about 1 hour, suggesting that 1.7 mm is the critical level. When 2.6 mm of liquid is added, the level stabilizes after only ½ hour. This indicates that the critical level is affected by more than just the contact angle. Since our calculations assume a static liquid configuration, this is most likely associated with the fact that the liquid is added in an uncontrollable way. If this is the case, the critical level is the maximum level that can be suspended, as previously suggested, but the measurement of the critical level only puts a lower bound on the actual contact angle. If we then apply equation (2.8), we find that the contact angle must be at least 32° to suspend 2.6 mm of liquid.
Figure 2.5.1. Superfluid helium level as a function of time above a cesium-coated platinum orifice for several different initial amounts of helium. After the successful run that is shown in Figure 2.4.6, the cryostat was warmed up to room temperature and the orifice was exposed to air for several weeks. For the runs shown here, the cryostat was cooled back down and the orifice was again coated with cesium.

Much more recently, Rolley and Guthman\textsuperscript{23} reported optical measurements of the contact angle of superfluid helium on a cesium-coated surface. They measured a contact angle of 25° at low temperature and 23° at 1.2 K, in very good agreement with our original data.

In these experiments, the film was evaporated at 77 K using the same type of source that we used. This supports the theory that surface roughness affects the contact angle.
2.6. Conclusions

We have demonstrated that the non-wetting of superfluid helium on cesium-coated surfaces can be used to suspend a 2.6 mm layer of superfluid helium over a hole 70 µm in diameter. We use our experimental estimate of a critical depth for this suspension to make an experimental measurement of the contact angle of superfluid helium on cesium of at least 32° at 1.2 K.

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3. Properties of the Dilution Refrigerator

3.1. Background

After demonstrating the suspension of superfluid helium using cesium-coated surfaces at 1.2 K, it was clear that the condensate experiment was feasible. The next problem was to create and detect helium atom beams that will be used to study the suspended superfluid layer. The beams must travel from the source to the detector without being scattered by other gas atoms in the cell. This means that the mean free path of a helium atom in the cell should be much greater than the path length it will travel. The expected distance between source and detector is of the order of a few centimeters. Since we must have bulk helium in the cell to perform the condensate experiment, the mean free path of a helium atom traveling through the cell is determined by the vapor pressure of liquid helium at the cell temperature. The mean free path is given by

\[ l = \frac{kT}{\sigma P}, \]  

(3.1)

where \( l \) is the mean free path, \( \sigma \) is the cross section for collisions between helium atoms at low temperature, and \( P \) is the saturated vapor pressure of helium at that temperature. The mean free path calculated from this formula is shown in Figure 3.1.1 for the temperature region of interest. The vapor pressure as a function of temperature is known\(^1\), while the collision cross section is estimated to be about 100 Å\(^2\) based on the calculations of E. S. Meyer.\(^2\) From this we see that the mean free path is of the order of a meter at temperatures below .35 K.
Figure 3.1.1. Calculated mean free path as a function of temperature for helium atoms traveling through a cell containing bulk liquid helium.

In addition to the requirement that the helium beams travel ballistically through a vacuum, the temperature must also be low enough to observe the ballistic roton process after the helium atoms from the beam have impinged upon the surface of the superfluid. Since the superfluid layer is expected to have a thickness of the order of 2 mm, we must have a mean free path for rotons traveling through the superfluid of the order of 1 cm. According to calculations by Wyatt\textsuperscript{3} the mean free path is greater than 1 cm below 100 mK. The only type of cryostat that will cool an experiment to this temperature and will operate continuously is a dilution refrigerator.
3.2. The Dilution Refrigerator System

Until 1965, the lowest temperature obtained with a continuous refrigeration method was 0.3 K, which can be achieved with a $^3$He refrigerator. In a $^3$He refrigerator, pure $^3$He gas is condensed into a cryostat in a chamber called the $^3$He pot. The liquid is then pumped out of the $^3$He pot and cooling occurs through the latent heat of evaporation of the liquid. The gas that is pumped out can be condensed back into the $^3$He pot by circulating through a return line that is in good thermal contact with another chamber, referred to as the 1 K pot, that is maintained at 1.2 K by pumping on liquid $^4$He. This method allows one to cool down to 0.3 K, at which point the vapor pressure of $^3$He becomes very small.

In 1962 a new technique was proposed that utilized the heat of mixing of $^3$He and $^4$He for cooling, rather than the latent heat of evaporation. Refrigerators that use this technique are called dilution refrigerators. The first dilution refrigerator was demonstrated in 1965 and achieved a minimum temperature of 0.22 K. Since that time, the performance of such refrigerators has been greatly improved and the lowest temperature achieved using only a dilution refrigerator is 2 mK. $^4$

The operation of a dilution refrigerator is similar to that of a $^3$He refrigerator with one extra cooling stage. The $^3$He pot is replaced with a chamber known as the still and the additional cooling stage is called the mixing chamber, as shown in Figure 3.2.1. A gas mixture of an appropriate ratio (usually about 25% $^3$He) is condensed into the still and
fills the mixing chamber and the still. The liquid mixture is pumped from the still and
the latent heat of evaporation from the liquid causes the initial cooling, just as in a $^3$He
refrigerator. However, when the temperature reaches about 0.6 K, the mixture
undergoes a phase separation into one phase pure $^3$He and the other phase $^4$He with
about 6% $^3$He. Since the $^3$He-rich phase is lighter, it will sit on top of the dilute phase. If
the ratio of the $^3$He/$^4$He mixture is correct and the total amount of liquid is correct, the
still pumping line will extend down through the $^3$He-rich phase and into the dilute
phase. Thus the mixture in the still will be at 0.6 K and will consist mainly of $^4$He with
a small amount of $^3$He. However, at this temperature the vapor pressure of $^4$He is
negligible, while the vapor pressure of $^3$He is 0.6 Torr.\textsuperscript{5} As the $^3$He gas is pumped out of
the still, the concentration of $^3$He in the still decreases. The system is no longer in
equilibrium and an osmotic pressure develops which causes $^3$He atoms to cross over
from the $^3$He-rich phase to the dilute phase. It is the mixing of the $^3$He and the dilute
phase which causes cooling in the dilution refrigerator. As the $^3$He is continuously
pumped out of the still, the mixing chamber cools to a much lower temperature than the
still. However, the still continues to cool due to the latent heat of evaporation of the
atoms. The circulation rate, and therefore the cooling power of the refrigerator, depends
on the vapor pressure of $^3$He at the still temperature, so the still must be heated to
maintain a high circulation rate. If the refrigerator is operated continuously, the gas
must be circulated back into the mixing chamber after passing through heat exchangers
and an appropriate impedance. The design of the heat exchangers determines the base
temperature of the cryostat. Some cryostats have several sintered silver step heat
exchangers in addition to counterflow heat exchangers. The most important factor in
determining the cooling power of the refrigerator is the circulation rate, which in turn depends on the type of pump (or pumps) used for mixture circulation.

Figure 3.2.1. Diagram of the basic elements of a dilution refrigerator. The helium mixture separates into concentrated and dilute phases of liquid $^3$He. $^3$He gas is pumped out of the dilute phase in the still through the $^3$He pump out line and is then introduced back into the concentrated phase after passing through heat exchangers at each refrigeration stage. Cooling occurs when $^3$He moves through the boundary between the concentrated and dilute phases.
We purchased a Janis Research Co., Inc. (Wilmington, MA) model CF-25 dilution refrigerator insert. The original specifications for the refrigerator were a base temperature of 50 mK or less and a cooling power of at least 35 µW at 100 mK. A cryostat with higher cooling power would make our experiments easier to design, but this would bring the cost much higher. As part of this purchase, we also obtained a 10-foot long 3” inner diameter flexible stainless steel pumping line, an Alcatel 2063H two-stage, sealed mechanical pump and a Precision Cryogenics aluminum-fiberglass dewar. In September 1996, I tested the dilution refrigerator at the factory using a gas handling system that was manufactured by Janis Research Co. The base temperature was measured to be 42 mK and the cooling power at 100 mK was 60 µW. A schematic of the dilution refrigerator insert and dewar assembly is shown in Figure 3.2.2.
Figure 3.2.2. Schematic drawing of the dilution refrigerator insert purchased from Janis Research Co., Inc. Used with permission.
Samples to be cooled by the refrigerator are mounted so that they are in good thermal contact with the mixing chamber, which is at the bottom of the insert shown in Figure 3.2.2. When the sample is mounted, the 1 K shield is bolted onto the 1 K pot shown in the diagram. Thus, all of the cryostat elements below the 1 K pot are heated only by radiation from 1.2 K. After this the Inner Vacuum Can (IVC) is sealed to the 4 K flange with an indium o-ring, and the cryostat is inserted into the dewar. At this point the entire assembly is as shown in Figure 3.2.2. The dewar allows all of the parts of the cryostat to be cooled to 4.2 K by introducing liquid helium into the bath, which is the area inside the dewar but outside the IVC. The 1 K pot is operated by opening the 1 K pot needle valve to allow liquid helium to flow into the 1 K pot. When the needle valve is closed, helium from the bath enters the 1 K pot through the siphon, which extends about half of the way down the outside of the IVC. The 1 K pot pump should be a mechanical pump that can pump the helium gas out into a recovery system or to the atmosphere.

In order to operate the refrigerator, a gas handling system to circulate the $^3$He-$^4$He mixture is required. The system must allow the user to easily manipulate the flow of the mixture through the cryostat and it must also store the mixture when the cryostat is not running. Most important, it must not leak. A diagram of the gas handling system that was built for this refrigerator is shown in Figure 3.2.3. The helium gas mixture is normally stored in Mixture Storage Vessel #1. When the cryostat has been cooled to 4 K by transferring liquid helium into the dewar, the mixture is circulated through the liquid nitrogen cold trap using the $^3$He pump. The 1 K pot is filled with helium from the dewar using the needle valve shown in Figure 3.2.2 and then the 1 K pot pump valve is
opened until the 1 K pot temperature is measured to be about 1.2 K. The 1 K pot pump is not part of the dilution refrigerator gas handling system. It consists of a 150 cubic feet/min (cfm) Stokes pump that is located in another room and connected to a valve near the cryostat with a 5” pumping line. A 2” pumping line connects this valve to the 1 K pot pumping line connection at the top of the cryostat, which is also shown in Figure 3.2.2. When the 1 K pot is at a low enough temperature to condense the mixture, the mixture is pumped into the still through the 3” inner diameter pumping line. When it has condensed into the still, we begin circulating the mixture by pumping it out of the still through the cold trap and then back into the still through the still return line. The pressure at the still return line is monitored on G1 and is maintained below 5” Hg vacuum. The pressure in the still pumping line decreases as the cryostat cools until it reaches about 100 mTorr. At this point, the still may be heated to increase the $^3$He circulation rate.

Since the cooling power of a dilution refrigerator is directly proportional to the circulation rate, the system must be designed to maximize this rate. Many high cooling power dilution refrigerators use ultra-high vacuum pumps to obtain a higher circulation rate for a given still pressure. In this case we used only a single two-stage mechanical pump to circulate the mixture in order to save money. This pump has a very high circulation rate at moderate (0.2 Torr) pressures. In addition to a pump with a high circulation rate, we also need pumping lines with low impedance coming out of the still and into the front of the pump. For this purpose we used a 10’ long 3” inner diameter flexible stainless steel pumping line. The pumping line connects to the $^3$He still
pumping port shown in Figure 3.2.2 on one end, and the other side connects to a 3” copper tee, one side of which connects to the gas handling system at the point where the Pirani gauge is read. The other side of the copper tee connects to V1, a brass bellows valve with KF-50 flanges on each side. At the opposite side of V1 we have installed about 3’ of 3” diameter copper tubing, which runs into the pump alley. At this point a short length of flexible stainless steel tubing connects to pumping line to the front of the Alcatel $^3$He circulation pump to provide some vibration isolation between the rigid copper pumping line and the pump. Thus most of the pumping line is 3” in diameter, which allows for a very high circulation rate.
Figure 3.2.3. Diagram of dilution refrigerator gas handling system. Valves are indicated by the symbol \( \oplus \). The \( ^3 \)He pump is used to circulate the mixture through different valve configurations. The \( ^3 \)He pump is located in another room to prevent interference with the experiment due to vibrations. The elements to the right of the dashed line are not on the gas handling system itself, but are shown schematically to simplify interpretation of the diagram.

At the back of the pump the volume must be minimized, since this region will be maintained at about 15” Hg vacuum. If this volume is too large, much of the mixture will be in the pumping lines rather than in the still, which in turn requires more mixture to be used for a given internal cryostat volume. The back of the pump connects directly to a short length of flexible stainless steel tubing for vibration isolation, followed by a Balston CV-0112-371H oil filter. The oil filter is very important because any oil vapor
that gets through it will end up condensing in the still return line, which has very high impedance and can be easily plugged. The oil filter should be replaced every few years, depending on how often the cryostat is run. After the oil filter there is a copper sweat tee, one side of which goes to the point specified on the gas handling system in Figure 3.2.3. The other side of the tee is connected to an Omega PSW-118 pressure switch with an adjustable range from 5 to 30 PSI. The normal operational setting for this switch is 8 PSI. Thus, if the pressure at the back of the pump reaches 8 PSI over atmosphere, the pressure switch is tripped and the pump will shut off. This is very important for two reasons. First of all, it is bad for the pump to run with a pressure at its outlet of greater than an atmosphere because this can generate leaks. Also, if there are any leaks at any point at the back of the pump and the gas pressure is greater than an atmosphere, the mixture will leak out of the gas handling system.

All of the valves used in the gas handling system (except V1) are Nupro B-4HK-TW bellows valves. Copper tubing with ¼” outside diameter was soft soldered into each valve after removing the bellows assembly. All of the connections between valves were made by soft soldering copper sweat connectors onto the tubes using 50/50-lead/tin soft solder. The pressure gauges are McDaniel Model JUU compound mechanical gauges that measure pressure relative to the ambient atmospheric pressure. The specified accuracy of these mechanical gauges is 1% of the full scale. Their range is from 1 atmosphere to 30” Hg vacuum and 0 to 15 PSI above atmosphere. These gauges are connected to the gas handling system with ¼” VCO face seal fittings. The Pirani gauge,
Kurt J. Lesker model KJL-2000D, is used to measure the still pressure. Its range is from 2 Torr to 1 mTorr and its specified accuracy is ±3 mTorr.

In addition to the pressure switch described above, there are a number of features that have been designed into the gas handling system that prevent any part of the system from reaching a pressure that is too high. In Figure 3.2.3, the symbol \(\lessgtr\) indicates a check valve. A check valve is designed to open only when the pressure difference from one side of the valve to the other exceeds a specified value. The value of this pressure difference is indicated on the diagram and the direction in which the pressure difference is measured is indicated by the direction of the arrows. Thus if the pressure at any point in the gas handling system exceeds 15 PSI relative to vacuum (which is approximately 1 atmosphere) a check valve will open and let the mixture into Mixture Storage Vessel #2 until the pressure difference is less than 15 PSI. This has happened on a few occasions. If the pressure in Mixture Storage Vessel #2 were to exceed 80 PSI relative to atmospheric pressure, the gas in this storage vessel will be let out into the room to prevent an explosive condition. This could only occur if there were a leak into the gas handling system that caused a large amount of gas to condense into the cryostat and then this gas expanded into the gas handling system as the cryostat warmed.

One of the most important parts of the gas handling system is the liquid nitrogen cold trap. The mixture is always circulated through the cold trap to remove condensable gases and prevent them from condensing into the still impedance, since this has been known to cause plugging of the return line. In general, all cold traps are designed to maximize the surface area that is present in the cold trap. Putting either activated
charcoal or Zeolite in the main cold trap chamber is the general approach. Beyond this basic idea, there are no accepted standards for cold trap design. It has been suggested that a single liquid nitrogen cold trap is insufficient if a cryostat is to be run continuously for long periods of time. In this case, many cryostats are run with an additional liquid helium cold trap in series with the liquid nitrogen trap. I chose to make a liquid nitrogen cold trap that is efficient enough to make a liquid helium trap unnecessary. The design for this cold trap is shown in Figure 3.2.4. The top and bottom pieces are constructed from brass, while the main chamber is a 2” outer diameter copper tube. The 3/8” outer diameter gas inlet and outlet tubes are 0.01” wall stainless steel. The stainless steel tubes are silver soldered into the top brass flange and the bottom brass flange is silver soldered to the 2” copper tube. After filling the main chamber with Zeolite pellets and enclosing the Zeolite between several layers of brass screen, the top flange is soft soldered onto the copper tube. The brass screen prevents the Zeolite from getting into the pumping lines.
3.3. Procedure for Running the Dilution Refrigerator

The following is a detailed procedure to be followed by the user when cooling the dilution refrigerator system down to base temperature.

*Figure 3.2.4. Design of the liquid nitrogen cold trap used in the gas handling system.*
Cooling from 300 K to 77 K

1. Check all of the wiring and then bolt the 1 K shield (labeled radiation shield in Figure 3.2.2) onto the 1 K pot and seal the vacuum can to the cryostat flange with indium wire. Leak check the vacuum can (IVC.)

2. Insert the cryostat into the dewar and connect the pumping lines. Leak check the IVC and check the wiring again. Pump out the $^3$He/$^4$He mixture circulation lines for at least 2 hours.

3. Pressurize the 1 K pot with 2-3 PSI helium gas and check the IVC for leaks from the 1 K pot. Close the 1 K pot needle valve but open and close it a few times to keep it from freezing while cooling to 77 K. Leave the helium gas pressure on the 1 K pot until the liquid nitrogen is removed after reaching 77 K.

4. Pump out the IVC and flush it with nitrogen gas twice, then pump it out and fill it with 100 Torr nitrogen gas.

5. Transfer liquid nitrogen to the top of the dewar. Wait at least 8 hours or up to 24 hours to reach 77 K. Record the resistance of all of the thermometers a few times during cool down.

6. When at 77 K, pump out the IVC with the leak detector until the helium background is low. Look for a low temperature leak from the 1 K pot to the IVC.

7. Measure the impedance on the helium return line. To do this, pressurize the helium return line with 1 atmosphere of pure helium or with the mixture. Monitor the still pressure using the Pirani gauge. Expect about 0.1 Torr/min pressure change.

8. Open V11 to allow both sides of the impedance to reach 1 atmosphere of helium. This checks for leaks from the cryostat into the IVC.

9. Pump the helium gas out of the gas handling system.
Cooling from 77 K to 4K

1. Pressurize the bath with helium gas to remove the liquid nitrogen.
2. Fill the IVC with 2 Torr hydrogen exchange gas.
3. Clean the mixture. To do this, first fill the cold trap with liquid nitrogen. Then open valves 4 and 5, then 8. Turn on the $^3$He pump, open valve 9, and then slowly open valve 2 while watching the pressure at the back of the pump. Slowly transfer liquid helium into the dewar.
4. After circulating the mixture for about one hour, pump the mixture out of the cold trap. To do this, close V2, open V7, close V5 and V8 and then open V3. When the mixture is out and the pressure in the still is below $10^{-3}$ Torr, close all valves, warm up the cold trap and check the pressure.
5. When 4 K is reached, measure the resistance of all thermometers.

Cooling from 4 K to .04 K

1. Open the 1 K pot needle valve to the bath and begin pumping the 1 K pot to the desired resistance of 3 kΩ or 0.33 mMho.
2. Pump the mixture out of the dump into the still. To do this, open valves 4, 5, 11, 9, and 2, respectively.
3. When mixture has condensed close V11 and V2, open V10, and then open V1A to begin circulation.
4. When the condensing pressure is low (15” Hg), slowly open V1 to circulate at a higher rate.
5. When the still pressure is below 200 mTorr, begin heating the still (~ 8 mA).

Leaving the cryostat overnight

1. Turn off the mixing chamber heater and the still heater.
2. Close V1 and V1A to stop circulation. Open V4 and V5 to the cold trap. Open V11, V7, and V9 and leave V10 open so that the mixture in the still is open to the dump.
3. Turn off the Alcatel pump.
4. Make sure the cold trap is full of liquid nitrogen.
5. Check the helium level in the dewar and transfer if necessary.
6. Close the valve from the pump to the 1 K pot.
7. Open the 1 K pot needle valve to the bath to allow the 1 K pot to come to equilibrium with the bath.

**Cooling back down to base temperature**

1. Close the 1 K pot needle valve and open the 1 K pot pump valve until the 1 K pot reads ~0.33 mMho. (~1/2 turn on 3/8” valve)
2. Turn on the Alcatel pump. Close V7 and V10 and open valves 9, 2, 5, 4, and 11 to pump the mixture from the dumps into the still.
3. To start circulation, close V2 and V11 and open V10 and V10.
4. When the condensing pressure is ~ -20” Hg, gradually open V1 while keeping the condensing pressure below -15” Hg.

**Final shutdown to warm the cryostat**

1. Close V5 and V2 and open V11 and V7 to pump the mixture from the still into the dump.
2. Heat the still and the mixing chamber with 20 mA current.
3. Close the 1 K pot pump valve and open the 1 K pot needle valve to the bath.
4. When the still pressure is measured to be zero on the Pirani gauge, (after about 1 hour) close all of the valves on the gas handling system except valves 4, 10, and 11 so that the still is open to the cold trap. Turn off the still heater and the mixing chamber heater.
5. Fill the cold trap with liquid nitrogen.
6. Turn off the Alcatel pump.

### 3.4. Measured Properties of the Dilution Refrigerator System

The first time the cryostat was cooled to 77 K, the impedance of the still return line was measured. The return line was pressurized with one atmosphere of pure helium gas and the pressure was measured on the Pirani gauge. The pressure increased at a rate of about 0.1 Torr/minute. If the impedance starts to increase in subsequent runs, this is a sign that something is getting into the still return line. One of the most common problems in running a dilution refrigerator is an increase in the still impedance, which can ultimately lead to the impedance being plugged. This usually occurs when the liquid nitrogen cold trap is insufficient for the trapping of condensable gases, or when the oil filter at the back of the circulation pump needs to be replaced.

After cooling the cryostat down to base temperature for the first time, the temperature was measured with a calibrated Matsushita carbon resistance thermometer (CRT). The calibration of the thermometer is accurate to ±3 mK. The resistance of the thermometer was measured using a BTI Model 1000 Potentiometric Conductance Bridge. At the lowest temperature obtainable, the CRT conductance was measured to be 0.904 mMho, which corresponds to 43 mK. The mixing chamber was then heated with various amounts of power and the temperature of the mixing chamber was measured. This is equivalent to measuring the cooling power as a function of temperature. The data is
shown in Figure 3.4.1, along with a fit to a quadratic function. The cooling power at 100 mK for this system is thus 75 µW, which is slightly better than the data obtained from the factory test.

The cooling power of a dilution refrigerator has been calculated to be

\[ \dot{Q}(T) = 84\dot{n}_3 T^2, \]  

(3.2)

where \( \dot{n}_3 \) is the circulation rate in mole/s and \( T \) is the temperature in mK. Comparing (3.2) to the equation for the fit shown in Figure 3.4.1, we find that our circulation rate is 107 µmole/s, in agreement with the experimentally measured circulation rate of 100 µmole/s.
Figure 3.4.1. Dilution refrigerator cooling power as a function of temperature. The diamonds are the measured cooling power. The line is a fit to a quadratic function of the temperature.

6 A. Sawada, S. Inoue, Y. Masuda, Cryogenics 26, 486 (1986)
7 Zuyu Zhao, Janis Research Co., Inc., private communication
4. Superconducting Bolometers for the Detection of Helium Atoms

4.1. Bolometer theory

A bolometer is a device that can be used to measure extremely small amounts of heat. In our experiments the bolometer measures the energy flux that crosses its surface as a function of time. This is accomplished by selecting a material whose electrical resistance depends strongly on temperature. Bolometers can be used at room temperature or at low temperature. They are particularly well suited for use at low temperature because, for a given device, operation at lower temperature causes an increase in the two most important properties of a detector: sensitivity and speed. The bolometers discussed here, cryogenic bolometers, are designed for use at low temperatures.

There are two basic types of cryogenic bolometers, semiconductor bolometers and superconducting bolometers. Semiconductor bolometers are made from doped germanium or silicon wafers. These bolometers typically have sensitivity in the range of $10^4$ to $10^5$ V/W and a response time of the order of 1 ms. On the other hand, typical superconducting bolometers have sensitivity in the range $10^2$ to $10^3$ V/W and a response time of the order of 1 $\mu$s. Since we are interested in measuring the time of flight of atoms on the order of 1 $\mu$s, we will be using a superconducting bolometer.
Theoretically, the output signal of a bolometer, $V_{\text{bolo}}$, is proportional to the product of the number density of atoms, $n$, and the average velocity of the atoms, $\langle v \rangle$, assuming all of the atoms condense on the surface of the bolometer. Thus

$$V_{\text{bolo}} \propto n \langle v \rangle (E + E_A),$$

(4.1)

where $E$ is the kinetic energy of each atom and $E_A$ is the heat of adsorption of each atom. Each atom contributes an amount of energy equal to the sum of its kinetic energy and the adsorption energy for a given surface. As described in Chapter 2, in our experiments all of the surfaces in the cell that are not covered with cesium will be covered with a thin film of superfluid helium. A helium atom that condenses on the surface of the bolometer will give up an amount of energy equal to the sum of its kinetic energy and the latent heat of helium at that temperature, which is 7.15 K. This energy multiplied by the flux of atoms gives the power input to the bolometer. Ideally, the voltage signal from the detector will be proportional to this power.

Superconducting bolometers make use of the fact that the resistance of a superconductor changes rapidly when it goes through a transition from the normal to the superconducting state. The width of the transition varies greatly depending on the type of superconductor and the number of impurities in the material, but is usually in the range of a few mK. In order to make use of the transition, the bolometer must be maintained to within less than 1 mK of the transition temperature at all times. When there is no signal input to the bolometer, it can be held at its transition by heating the bolometer until its temperature is equal to its transition temperature. If the bolometer is heated by running a current through it, then an input signal from a flux of atoms will heat the bolometer, which will cause the
bolometer resistance to increase. The power input to the bolometer is $P_{\text{signal}} + I^2 R$, where $P_{\text{signal}}$ is the power input due to the flux of atoms and $I$ is the current that has been applied to heat the bolometer to its transition temperature. Since the resistance increases when $P_{\text{signal}}$ is applied, the second term also contributes to heating the bolometer even more, which causes the resistance to increase more. The end result is that if a constant current is used to heat the bolometer to its transition, any input signal will cause the bolometer to heat until it reaches the normal state. Clearly a more sophisticated method is needed to maintain the bolometer at its transition.

A circuit designed for this purpose is shown in Figure 4.1.1. $R_1$ and $R_2$ determine the gain of the operational amplifier (op-amp) shown in the figure. $R_0$ and $V$ determine the operating temperature of the bolometer. It is important to realize that the resistance $R_{\text{bolo}}$ is a strong function of temperature and the circuit relies on this fact for successful operation. If the voltage at the output of the op-amp is $V_{\text{out}}$ and the voltage at the positive input to the op-amp is $V_{\text{in}}$, the rules governing op-amp behavior dictate that $\frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_1}{R_c}$.

If we denote $\frac{V_{\text{out}}}{V_{\text{in}}} \equiv A$ we can then create a simplified diagram as shown in Figure 4.1.2.
Figure 4.1.1. Feedback circuit used to operate a superconducting bolometer. \( V_{\text{bolo}} \) is the voltage proportional to the bolometer signal. \( R_{\text{bolo}} \) is the resistance of the bolometer. \( R_1 \) and \( R_2 \) control the gain of the feedback circuit, while \( V \) and \( R_0 \) determine the operating temperature of the bolometer.

\[ A \equiv 1 + \frac{R_2}{R_1} \]

Figure 4.1.2. Simplified circuit equivalent to that shown in Figure 4.1.1, where

Since current cannot go through the amplifier, the same current that goes through \( R_{\text{bolo}} \) goes through \( R_0 \). We must have

\[ V_{\text{in}} = IR_0 + V \]

The current through the bolometer is
\[ I = \frac{V_{\text{out}} - V_{\text{in}}}{R_{\text{bolo}}}. \]  \hspace{1cm} (4.3)

Since the amplifier has a gain of A,

\[ V_{\text{out}} = AV_{\text{in}}. \]  \hspace{1cm} (4.4)

Substituting (4.4) into (4.3) gives

\[ V_{\text{in}} = \frac{IR_{\text{bolo}}}{(A - 1)}. \]  \hspace{1cm} (4.5)

Equating (4.5) and (4.2) gives

\[ I = \frac{V}{R_0 - \frac{R_{\text{bolo}}}{(A - 1)}}, \]  \hspace{1cm} (4.6)

and the power dissipated in the bolometer is

\[ P_{\text{feedback}} = \frac{\{V(A - 1)\}^2 R_{\text{bolo}}}{\{R_0(A - 1) - R_{\text{bolo}}\}^2}. \]  \hspace{1cm} (4.7)

If

\[ R_0(A - 1) < R_{\text{bolo}} \]  \hspace{1cm} (4.8)

then as \( R_{\text{bolo}} \) increases the power input to the bolometer decreases. This is precisely what is needed for stable operation of the bolometer. The quiescent operating point of the circuit is then adjusted by changing \( R_0 \) until the power input is such that the bolometer is maintained at its superconducting transition edge. If a signal heats the bolometer, the feedback circuit decreases the power input, which allows the bolometer to cool back to its operating temperature.
The rate at which the bolometer cools back to its operating temperature is determined by its thermal time constant.

Now that we know the power input to the bolometer as a function of $R_{\text{bolo}}$ and other adjustable parameters in the circuit, we can determine how the bolometer will react to a time-dependent signal. All of the power input to the bolometer must either change the bolometer temperature or be conducted to the cell, so if there is no external signal applied then

$$P_{\text{feedback}} = C \left( \frac{dT}{dt} \right) + G_0(T - T_0), \quad (4.9)$$

where $C$ is the heat capacity of the bolometer and $T_0$ is the cell temperature. At equilibrium we have

$$P_{\text{feedback}} \Big|_{T_{\text{bolo}}} = G_0(T_{\text{bolo}} - T_0), \quad (4.10)$$

where $G_0$ is the thermal conductivity from the bolometer to the cell and $T_{\text{bolo}}$ is the equilibrium bolometer operating temperature. If an external signal, $P_{\text{signal}}$, is applied to the bolometer, we get

$$C \left( \frac{dT}{dt} \right) + G_0(T - T_0) = P_{\text{signal}} + P_{\text{feedback}} \Big|_{T_{\text{bolo}}} + \left( \frac{dP_{\text{feedback}}}{dT} \right) \Delta T \quad (4.11)$$

Since the bolometer temperature will always be near the equilibrium temperature, $G_0$ will not change significantly. Therefore

$$G_0(T - T_0) = G_0(T_{\text{bolo}} + \Delta T - T_0) = G_0\Delta T + P_{\text{feedback}} \Big|_{T_{\text{bolo}}} \quad (4.12)$$

Inserting (4.12) into (4.11) we obtain
\[ C \left( \frac{d\Delta T}{dt} \right) + G_o \Delta T = P_{signal} + \left( \frac{dP_{feedback}}{dT} \right) \Delta T \] (4.13)

If we define

\[
G_E \equiv G_o - \frac{dP_{feedback}}{dT} \] (4.14)

then equation (4.13) can be written

\[
C \left( \frac{d\Delta T}{dt} \right) + G_E \Delta T = P_{signal} . \] (4.15)

Equation (4.15) describes a system characterized by a thermal time constant \( \tau = \frac{C}{G_E} \). (4.16)

The time constant of the system depends directly on the heat capacity of the bolometer and the thermal conductivity of the bolometer to the cell. It also depends on the value of the quantity \( \frac{dP_{feedback}}{dT} \), which is extremely sensitive to the nature of the superconducting transition and the values chosen for \( R_0 \) and \( A \) when selecting the bolometer operating conditions. In practice, \( R_0 \) and \( A \) can be adjusted to minimize the time constant of the bolometer.

The signal from the bolometer is obtained by measuring \( V_{out} \), the voltage at the output of the amplifier. If we substitute (4.6) into (4.5) and then substitute the result for \( V_{in} \) into (4.4), we get

\[
V_{out} = \frac{VR_{bolo}A}{(A-1)R_0 - R_{bolo}} . \] (4.17)
Since \((A - 1)R_0 < R_{bolo}\) by (4.8), \(V_{out}\) is negative. \((A - 1)R_0\) is chosen to be as close to \(R_{bolo}\) as possible to maximize the signal. The signal is only a function of \(R_{bolo}\), but \(R_{bolo}\) is itself a function of \(T\). In principle, given the temperature dependence of \(R_{bolo}\), equations (4.13) and (4.7) can be solved for \(R_{bolo}\) as a function of time for a given input signal and the resulting equation can be inserted into (4.17) to obtain the bolometer signal as a function of time. This series of coupled differential equations is most easily solved numerically. A simulation\(^3\) which allows calculation of the bolometer output for a given input signal will be described in section 4.3.

The two parameters most widely used to describe bolometer performance are the time constant and the Noise Equivalent Power (NEP). The Sensitivity, \(S\), is given by the ratio of the voltage output, \(V_{out}\), divided by the input power, \(P_{signal}\). The Sensitivity can in principle be calculated from equation (4.17). The NEP is then given by

\[
NEP = \frac{V_{noise}}{S} = \frac{V_{noise}}{V_{out}} P_{signal},
\]

(4.18)

where \(V_{noise}\) is the voltage noise per \(\sqrt{Hz}\). The voltage noise can be estimated from the operating conditions of the bolometer. The Johnson Noise is given by

\[
\sqrt{4kTR} = 4nV / \sqrt{Hz}
\]

(4.19)

where \(R\) is the parallel resistance of the resistors shown in Figure 4.1.1 as seen at the inputs of the op-amp (about 1 k\(\Omega\)), and \(T\) is in this case room temperature. The Johnson noise of the bolometer itself is negligible due to its low resistance and low temperature. Thermal fluctuations of the heat bath also cause bolometer noise.\(^4\) The noise due to thermal fluctuations is
\sqrt{4kT_{\text{bolo}}^2 G_0} = 7 \times 10^{-15} W / \sqrt{Hz} \quad (4.20)

where all of the variables have their usual meaning. Based on the thermal conductivity of
the copper leads connecting the bolometer to the bolometer mount, \( G_0 \) is estimated to be
10 \( \mu \)W/K. \( T_{\text{bolo}} \) is assumed to be 0.3 K. The final voltage noise source in our circuit is the
voltage noise of the op-amp itself. In our case we are using an OP-37 op-amp, which has
a rated voltage noise of \( V_n = 3nV / \sqrt{Hz} \) and current noise of \( i_n = 0.5 \text{pA} / \sqrt{Hz} \). Since all
of these noise sources are independent, they add in quadrature, so the total expected
voltage noise for our circuit is \( V_n = 5nV / \sqrt{Hz} \). The sensitivity can be estimated from the
bolometer simulation that will be discussed in section 4.3. The result is \( S = 10^3 V / W \),
which gives an estimated NEP of \( 10^{-12} W / \sqrt{Hz} \). This means that over the 1 MHz
bandwidth of interest, an incoming beam of \( 10^{-9} \) Watts will have a signal to noise ratio of
1.

4.2. Titanium Bolometers

The superconducting bolometers we will use consist of a thin film of superconducting
material deposited onto a substrate. Conducting leads make contact to the
superconducting film. We have chosen titanium, which has a transition temperature of
about 0.4 K, for the superconducting material of our bolometers. A bolometer operating
at 0.4 K will have good thermal conductance to a cell with a temperature ranging from 0.1
K to 0.3 K, allowing the detector to cool quickly back to its operating temperature after
being heated by an incident beam. The low heat capacity and high thermal conductivity
of sapphire at low temperature make it an appropriate substrate.
We have developed a technique to make bolometers using titanium and 1 mm diameter sapphire substrates. Two 40 nm thick silver contact pads are thermally evaporated onto the substrate. Conducting leads made from #46 magnet wire are attached to the contact pads using silver epoxy with the aid of a micromanipulator. Titanium films of thickness ranging from 20 to 40 nm are then deposited onto the substrate, contact pads and leads. We deposited titanium films both by thermal evaporation and by sputtering. The bolometers are attached to the copper bolometer mounts as shown in Figure 4.2.1. A mounting wire is epoxied to the back of the bolometer substrate using Stycast 2850 FT epoxy. The mounting wire is sandwiched between the bolometer mounting plate and the mounting bracket to hold the bolometer in place. The leads are also epoxied to the mount to provide strain relief. The leads are then soldered to a 4-wire electrical connector that is epoxied to the bolometer mount. Finally, the mounting bracket is bolted to the mixing chamber of the dilution refrigerator to provide thermal contact.
Figure 4.2.1. Diagram of copper bolometer mounts. A thin copper mounting wire is epoxied to the back of the bolometer and is inserted between the mounting plate and the mounting bracket. The mounting plate is bolted to the mounting bracket so that the mounting wire holds the bolometer in place. The leads are epoxied to the mounting bracket for strain relief. The mounting bracket is then bolted to the mixing chamber of the dilution refrigerator.

We found that thermally evaporated films did not superconduct when cooled to 43 mK. The resistance of the sputtered films was measured as a function of temperature in two different experiments. The superconducting transition that was measured for two of the sputtered films is shown in Figure 4.2.2. The transition temperature is 0.44 K for both films. This is slightly higher than the bulk transition temperature of titanium at 0.39 K, but is consistent with other published results for sputtered films.⁵
The resistance of the films shown in Figure 4.2.2 was measured using a 4-wire measurement technique. A constant voltage was applied across a circuit containing the titanium film in series with a large variable resistor. The resistor was chosen so that its resistance was much greater than the resistance of the film. This is equivalent to a constant current source. The voltage across the film was monitored with a Keithley 2000 Multimeter. Currents of 1 µA and 0.1 µA were used to verify that the measured resistance was the same for each current. The temperature was regulated with a BTI Model 1000 conductance bridge, which contains a temperature controller with Proportional, Integral, and Differential (PID) feedback settings. The temperature
controller was made to adjust the temperature by applying current to a heater that is mounted directly on the mixing chamber of the refrigerator. The drift in temperature was ±3 mK. The controller was set to adjust the heater power until the conductance of the calibrated Matsushita carbon resistance thermometer (CRT) reached a specified value. In order to evaluate the film resistance data, it was necessary to fit the calibration points of the CRT to a functional form and then calculate the temperature corresponding to the CRT conductance at which the cryostat was regulated for that measurement. The data points from the original thermometer calibration are shown in Figure 4.2.3. The data were only fit for temperatures from 0.3 K to 1 K. Below 0.3 K, the temperature dependence of the resistance of this type of carbon resistance thermometer is expected to be completely different, so another curve should be fit to this data if necessary.
Figure 4.2.3. Calibration data for the Matsushita carbon resistance thermometer used to measure the cryostat temperature. The squares are the calibrated points provided with the thermometer. The line is a fit to the data that was used to evaluate the temperature for any resistance measurement in this temperature range.

All of the measurements shown above were made without helium in the experimental cell. However, as demonstrated by equations (4.9) to (4.16), the bolometer properties are very sensitive to the heat capacity. The heat capacity shown in those equations includes the titanium film, the sapphire substrate, and the helium film that will be covering the bolometer in our beam experiments. We built an experimental cell that allows us to do experiments in the presence of a thin film of superfluid helium. The details of the cell design will be presented in Chapter 5. The titanium bolometers were mounted in the experimental cell and helium was added until a thin film of superfluid covered the bolometers. An instrument containing the circuit shown in Figure 4.1.1 was constructed
in such a way that the user could adjust $R_0$, $V$, and $G$. The cell temperature was maintained at 290 mK, $G$ was set to a gain of 10, and $V$ was set at its smallest value. $R_0$ was adjusted and $V_{\text{out}}$ and $V_{\text{bolo}}$ were measured for each value of $R_0$. The resistance measurements for a 40 nm and a 20 nm thick titanium film on a 2.5 mm diameter sapphire substrate are shown in Figure 4.2.4 and Figure 4.2.5, respectively. At any point along the curve we can calculate the power dissipated in the bolometer, and since the resistance of the bolometer as a function of temperature is known, we can use equation (4.10) to calculate $G_0$. According to Figure 4.2.4, when $R_{\text{bolo}} = 13 \, \Omega$, $P_{\text{feedback}} = 168 \, \text{nW}$, $T_0 = 290 \, \text{mK}$, and from Figure 4.2.2, $T_{\text{bolo}} = 440 \, \text{mK}$, so finally we have $G_0 = 1 \, \mu\text{W} / \text{K}$. This is consistent with our original estimate of $10 \, \mu\text{W} / \text{K}$, since our estimate assumed perfect thermal contact between the copper wire and the bolometer mount. In reality the thermal contact is probably very poor because the wires are insulated and the insulation is thermally anchored to the bolometer mount with epoxy.
Figure 4.2.4. Measured resistance of a 40 nm thick sputtered titanium film on a 2.5 mm diameter sapphire substrate as a function of $R_0$, an adjustable parameter in the bolometer feedback circuit. Adjusting $R_0$ allows the user to choose the quiescent operating temperature of the bolometer. The cell temperature for these measurements was 290 mK.
Figure 4.2.5. Measured resistance of a 20 nm thick sputtered titanium film on a 1 mm diameter sapphire substrate as a function of $R_0$, an adjustable parameter in the bolometer feedback circuit. Adjusting $R_0$ allows the user to choose the quiescent operating temperature of the bolometer. The cell temperature for these measurements was 290 mK.

4.3. Bolometer Simulation

In order to calculate the response of the bolometer to an input signal, one could simply solve equation (4.13) to find the temperature of the bolometer as a function of time. Then using the bolometer resistance as a function of temperature shown in Figure 4.2.2, $R_{bolo}$ can be calculated as a function of time. Finally, equation (4.17) gives the bolometer signal as a function of time for a given input signal. These equations can be solved numerically, but one must take into account the fact that the heat capacity $C$ given in the above equations is different for each element of the bolometer and there may be a
temperature gradient between each element, so we must use a more detailed description of the bolometer to get an accurate simulation.

![Block diagram of the elements of the bolometer system.](image)

**Figure 4.3.1.** Block diagram of the elements of the bolometer system. A sapphire substrate is coated on one side with a thin film of titanium. The copper conducting leads, with conductance $G_0$, provide the main thermal connection to the cell. The bolometer and leads are covered with a thin film of helium for the experiments that will be described here. When helium atoms impinge upon the detector, the helium film is heated to temperature $T_1$. The temperature of each element is then calculated by solving a series of coupled differential equations.

The bolometer consists of 4 basic elements, which are shown in Figure 4.3.1. The helium and titanium film temperatures are $T_1$ and $T_2$, respectively. The substrate temperature is denoted $T_3$ and the cell is maintained at temperature $T_0$. These temperatures are all different due to the thermal boundary resistance at each surface. Equation (4.9) can be expanded to describe the temperature evolution of the titanium film as

$$C_2 \frac{dT_2}{dt} = \frac{A_{12}}{k_{12}} (T_1^4 - T_2^4) + \frac{A_{23}}{k_{23}} (T_3^4 - T_2^4) + P_{\text{signal}} + P_{\text{feedback}} - G_0 (T_2 - T_0).$$

(4.21)

$P_{\text{feedback}}$ depends on $T_2$ through the temperature dependence of $R_{\text{bolo}}$ [see equation (4.7)].

If $T_a$ denotes the temperature of one element and $T_b$ is the temperature of another element in thermal contact with $T_a$, then the thermal boundary resistance between these elements is $k_{ab}$, and the contact area is defined as $A_{ab}$. The temperature dependence of the thermal
boundary resistance used in these equations is based on experimentally measured values for each type of boundary.\(^7\) Similarly, the helium film temperature is described by

\[
C_1 \frac{dT_1}{dt} = \frac{A_{12}}{k_{12}}(T_2^4 - T_1^4) + \frac{A_{13}}{k_{13}}(T_3^5 - T_1^5) - P_{\text{evap}}, \tag{4.22}
\]

where \(P_{\text{evap}}\) is the power lost due to evaporation of the helium from the film. Finally, the substrate temperature evolution is given by

\[
C_3 \frac{dT_3}{dt} = \frac{A_{13}}{k_{13}}(T_1^5 - T_3^5) + \frac{A_{23}}{k_{23}}(T_2^4 - T_3^4). \tag{4.23}
\]

Thus for a given input \(P_{\text{signal}}\), these coupled differential equations can be integrated numerically to find the temperature evolution of the film. From this the resistance of the bolometer as a function of time can be found, and thus we obtain \(V_{\text{out}}\) as a function of time for an arbitrary input power. The simulation was run using the measured properties of the titanium bolometer shown in Figure 4.2.4. The input signal is a 1 \(\mu\)s, 100 nW square pulse. The bolometer signal as a function of time is shown in Figure 4.3.2. The sensitivity of the bolometer can be estimated by calculating \(V_{\text{out}} / P_{\text{signal}}\). The estimated sensitivity from the simulation is \(S = 10^3 \, \text{V/W}\) with a time constant of less than 1 \(\mu\)s.
Figure 4.3.2. Simulated bolometer signal for a 1 µs, 100 nW square pulse input.

1 M. Zen in Atomic and Molecular Beam Methods, Giacinto Scoles, ed. (Oxford, New York, 1988)
3 Keith A. Lidke, private communication
5. **Ultra-Cold Helium Atom Beams**

5.1. **Background**

In our planned experiment we will use helium atom beams to probe a suspended slab of superfluid helium. These helium atom beams must have translational energies on the order of a few degrees Kelvin in order to produce the processes that we are interested in observing. In order to make time of flight measurements, the beams must be pulsed. We would also like to make the beams as narrow in time as possible to provide the best time resolution. As mentioned in Chapter 1, we would like to be able to distinguish a picosecond process from a 10 µs process. Ideally we would use beams that are less than 10 µs long. This has never been demonstrated and may not be possible. However, since we are interested in determining whether any atoms arrive at our detector before the 10 µs delay expected for a roton signal, it would be possible to use a beam that has a leading edge that is less than 10 µs long to distinguish the condensate-mediated process from the ballistic roton process.

It should also be possible to distinguish the condensate-mediated process from a roton process by the known temperature dependence of the roton process. Since the mean free path of rotons gets much shorter as the temperature is increased above 100 mK, any signal due to the ballistic roton process will rapidly decay as the temperature is increased. Any remaining signal can then be studied in detail by varying the properties of the helium atom beams that will be discussed in this chapter. To do this, we would like to be able to
change the average velocity of the beam and the beam width. In particular we would like
to be able to create beams with a very narrow energy distribution so that we can study the
processes of interest as a function of incoming beam energy.

5.2. Helium Atom Beams From a Supersonic Expansion

If a beam of helium atoms has a density such that the collision rate between atoms in the
beam is high, the atoms in the beam will reach internal thermal equilibrium. If this is the
case, we can assign a temperature to the beam. The temperature of the beam is
determined by its velocity distribution. In an ideal gas, the velocity distribution as a
function of temperature is

\[ P(v) = \frac{1}{2\pi} \left( \frac{m}{kT} \right)^2 \exp\left( -\frac{mv^2}{2kT} \right), \quad (5.1) \]

and \( P(v)dv \) is the probability of finding an atom with its velocity within \( dv \) of \( v \). If the
velocity distribution of the beam can be measured, then fitting the above function to the
measured distribution gives a measure of the internal temperature of the beam. Normally,
one would expect this temperature to be the same as the beam source temperature.
However, under certain conditions it has been found that collisions between atoms in
beams of high density can cause cooling of the beam, so that the value of \( T \) found from
the measured velocity distribution is much lower than the source temperature.
Helium atom beams that exhibit such cooling were first studied using room temperature atomic beam sources. In these experiments, a gas at high pressure is allowed to freely expand into a vacuum. This type of expansion is referred to as a supersonic expansion because the beam reaches speeds greater than the speed of sound in a gas. If we assume an isentropic expansion for an ideal gas, we can calculate the expected properties of the resulting beam. Since the gas expands from a constant pressure source, its enthalpy is converted into kinetic energy as it expands. ¹ Thus the quantity

\[ H_0 = H + \frac{1}{2} mv_{cm}^2 \]  

(5.2)
is conserved throughout the expansion, where \( v_{cm} \) is the center of mass velocity and

\[ v_{cm}^2 = \frac{2}{m}(H_0 - H) = \frac{2}{m} \int \rho dT. \]  

(5.3)

For an ideal gas this becomes

\[ v_{cm} = \sqrt{\frac{2}{m} \left(\frac{\gamma}{\gamma - 1}\right)} \frac{k(T_0 - T_{int})}{m} = \sqrt{\frac{5k(T_0 - T_{int})}{m}} \]  

(5.4)

where \( T_0 \) is the source temperature and \( \gamma = 5/3 \) for helium. For helium originating from a source at room temperature, \( v_{cm} = 1800 \text{ m/s} \). The speed of sound in a gas is given by

\[ c = \sqrt{\frac{kT}{m}}. \]  

(5.5)

If we define the Mach number as \( M \equiv \frac{v_{cm}}{c} \), we can solve for the internal temperature of the beam

\[ T_{int} = \frac{T_0}{1 + \frac{M^2(\gamma - 1)}{2}}. \]  

(5.6)

Since the density in an isentropic expansion must conserve the quantity \( Tn^{1-\gamma} \), we have
\[ n = n_0 \left(1 + \frac{M^2(\gamma - 1)}{2}\right)^{-\frac{1}{\gamma-1}}. \]  

(5.7)

For a supersonic expansion, \( M \) depends on the reduced distance \( x \equiv r/d \), where \( r \) is the distance that the beam has traveled from the orifice out of which the beam is expanding, and \( d \) is the orifice diameter. The Mach number as a function of reduced distance for a gas with \( \gamma = 5/3 \) has been calculated\(^1\) and is given by

\[ M = x^{2.5} \left(3.232 - \frac{0.7563}{x} + \frac{0.3937}{x^2} - \frac{0.0729}{x^3}\right). \]  

(5.8)

Equation (5.6) gives the internal beam temperature as the beam expands outward from the source, but it is only valid while the beam density is high enough to maintain thermal equilibrium. When the beam is no longer in internal equilibrium but 2-body collisions continue to narrow the velocity distribution, it has been argued that it is then possible to divide the kinetic degrees of freedom into transverse and longitudinal components. This is known as the transition regime. A theory describing the behavior of a supersonic expansion in the transition regime was developed by Toennies and Winkelmann.\(^2\) They predict that the internal beam temperature from a room temperature expansion will saturate at about 0.7 mK. Pulsed helium beams from a room temperature source have achieved internal temperatures of less than 1 mK,\(^3\) which is consistent with this prediction.

Similar cooling effects were later observed\(^4\) for helium atom beams originating from a superfluid film at low temperature. In this experiment, a 10 cm diameter copper cell is cooled to 250 mK in a dilution refrigerator and helium is added to the cell until a thin
film of superfluid covers the cell walls. Two identical bolometers consisting of a 1 cm x 1.5 cm x 50 µm thick sapphire plate with a 750 x 750 x 250 µm neutron transmutation doped germanium bolometer chip mounted on the back of the plate were set up 8 cm apart with the sapphire plates facing each other. Electrical heating pulses are sent through one of the Ge chips, causing the temperature of the sapphire plate to rise. This increase in substrate temperature heats the thin film of superfluid covering the plate, which causes an increase in the vapor pressure of the helium film according to the equation

\[ n_{\text{vap}}(T_{\text{film}}) = \frac{(2\pi m k T_{\text{film}})^{3/2}}{h^3} \exp\left(-\frac{7.15K}{T_{\text{film}}}\right). \]  

(5.9)

As the film temperature approaches 1 K, the mean free path for the evaporated helium atoms is of the order of 1 µm (Figure 3.1.1.) The evaporated atoms will achieve internal equilibrium at this density, but they will also expand outward from the source into the vacuum in the rest of the cell. This is similar to the situation encountered in the room temperature isentropic expansions mentioned earlier, but in this case the source temperature is much lower. For a film temperature of 1 K, equation (5.4) gives a maximum velocity of 100 m/s. In the experiments of Meyer et. al., the film was heated with pulses of varying powers for 200 µs. For powers 200 µW and lower, the helium film heated to about 0.6 K and the beam shape could be fit to the Maxwell-Boltzmann distribution of equation (5.1) for a source temperature of 0.6 K. For higher power pulses, significant beam cooling was observed. When a 1.2 mW pulse was used, the helium film was heated to 0.85 K and the beam internal temperature from the fit was found to be approximately 1 mK. The center of mass beam velocity was measured to be
\( v_{cm} = 80 \text{ m/s} \), in agreement with equation (5.4). This may have been the first demonstration of a supersonic expansion from a low temperature liquid film.

Shortly after these results were reported, an experiment performed by Mulders and Wyatt\(^6\) demonstrated cooling of a helium atom beam to even lower temperatures. They used a much smaller source and a longer distance from source to detector. The source used was a .3 mm square, 30 nm thick chromium heater. The detector was a superconducting zinc bolometer. They report measurements of beams with source-detector distances of 13 cm and 5.7 cm. With a heater power of 200 \( \mu \text{W} \), the Cr heater was sent square pulses with lengths varying from 50 \( \mu \text{s} \) to 800 \( \mu \text{s} \). For the shortest pulse, the detected signal has a full width at half maximum (FWHM) of about 150 \( \mu \text{s} \) at a distance of 5.7 cm. For the longest pulse, the FWHM increases to about 800 \( \mu \text{s} \).

The beams detected at this distance are not narrower in time than the pulse used to generate the beam. However, if one were to assume that equation (5.9) applies at all times, the expected signal width could be calculated from the temperature of the source. In this case the source temperature is not known, but can be estimated from the time of flight data by calculating \( v_{cm} \) and using equation (5.4) to find \( T_0 \). For the narrowest pulse, I find \( v_{cm} \) to be about 80 m/s, so the helium film reaches a temperature of about 0.7 K for a 50 \( \mu \text{s} \), 200 \( \mu \text{W} \) pulse under these conditions. According to the calculations of Meyer,\(^5\) the width of the signal according to equation (5.9) should be about 600 \( \mu \text{s} \). This suggests that the beam has narrowed due to collisions. This theory is supported by the fact that at lower power, and therefore lower beam density, the beam width can be fit to a Maxwell-
Boltzmann distribution that corresponds to the source temperature predicted by equation (5.4). The theory is also supported by the data obtained by Mulders and Wyatt for a 200 μs, 300 μW heat pulse detected at a distance of 13 cm. The FWHM of the beam is 35 μs, indicating significant cooling. An ideal isentropic expansion from a source of this diameter would be expected to have an internal temperature of 100 μK, but the internal temperature determined by fitting this data to a Maxwell-Boltzmann distribution is 700 μK. The discrepancy is most likely due to the fact that the density decreases rapidly as the beam cools and thermal equilibrium is not maintained within the beam.

5.3. Experimental Apparatus

We designed an experiment to generate ultra-cold helium atom beams using the heat pulse technique described above. A diagram of the cell is shown in Figure 5.3.1. The cell consists of a 2.75” outer diameter copper tube with 0.25” wall thickness and 0.5” thick top and bottom flanges that are connected to the cell body with an indium o-ring seal. Before attaching the flanges to the cell body, the sources are attached to the source mounts, which are mounted using the same technique as the bolometers. The bolometer mounts are described in Chapter 4. The source mounts are then bolted to the bottom flange of the cell. Four wires that lead to the bottom wiring feedthrough are attached to the source so that electrical current can be run through the heater. The bottom flange is sealed to the cell body. The bolometer mounts are then bolted to the top flange and four wires that lead to the top wiring feedthrough are attached to each bolometer. Finally, the top flange is sealed to the cell body. The cell should now be sealed at all points except for
the wiring and capillary feedthroughs. These feedthroughs also seal to their respective flanges with an indium o-ring.

Figure 5.3.1. Diagram of the experimental cell used for the helium atom beam experiments. The cell is made of copper and is bolted directly to the mixing chamber of the dilution refrigerator. Helium is added to the cell through one of the capillary feedthroughs shown in the diagram. Electrical heating pulses are sent to one of the sources shown at the bottom of the cell and helium atoms are detected with one of the titanium bolometers shown at the top of the cell.
The capillary flange consists of a copper flange that seals to the cell flange with an indium o-ring. A 0.016” hole is drilled through the center of the flange. The capillary used was 0.014” OD, 0.004” ID copper-nickel tubing. One end of the CuNi tubing was cut using a sharp razor blade and covered with aquadag, a colloidal suspension of graphite that is not wet by solder. The CuNi tubing was then soldered into the flange and tested for leaks and to make sure gas would flow through it. The rest of the CuNi tubing was thermally anchored to the mixing chamber, still, 1 K pot, and the 4 K flange of the dilution refrigerator. At the 4 K flange each capillary was soldered to a 1/16” stainless steel tube that led to room temperature and into a Nupro bellows valve at the top of the cryostat.

One of the most difficult problems we faced was making a wiring feedthrough that allowed 16 wires into the cell without causing a leak. For the first feedthroughs, a 0.005” wall 0.25” OD stainless steel tube was soldered into a copper flange that was designed to seal to the cell flange with an indium o-ring. The 16 twisted pairs were untwisted for a length of about 2 mm and then they were inserted into the stainless steel tube. The wires were held in place by a clamp and the tube was filled with Stycast 2850 FT epoxy. The seal for each wiring feedthrough was then tested with a helium leak detector at room temperature and at 77 K and no leak was found.

After cooling the dilution refrigerator down to 45 mK with the cell bolted to the mixing chamber it was determined that the new wiring and capillaries did not represent a significant heat load on the system. However, when helium gas was added to the cell, the
cryostat temperature would quickly increase. This is indicative of a leak from the cell to the IVC. We tested this by pumping on the IVC with the leak detector while adding helium to the cell. As the cell was cooled below 2 K, a signal began to appear on the leak detector. This is an indication of what is known as a superleak. A superleak is a leak that is so small that it only appears when superfluid helium is present. There is no way to detect where a superleak is in the cell because it cannot be detected at room temperature. It seemed likely that the leak was in the wiring feedthrough, so we warmed up the cryostat and replaced the wiring feedthroughs with blank flanges made of brass. This time the cryostat cooled to 290 mK with helium in the cell. We needed to make wiring feedthroughs that would not leak, so we changed our technique for making the flanges.

The new wiring flanges were made from a 11/16” diameter brass rod. The brass was cut so that it would seal to the cell flange and a thin wall stainless steel tube was soldered to the brass flange. An array of holes was cut into a 1 mm thick, 0.25”diameter piece of Teflon. One strand of copper wire with polyamide insulation was threaded through each hole and then that wire was threaded through another identical Teflon piece about 1 cm away. The wires did not touch each other at any point along this array. The wire array was inserted into the stainless steel tube and a Teflon mold was placed around the tube. Stycast 2850 FT epoxy was then added to the mold until the mold was filled to the top. The assembled feedthrough was then baked at 100 °C for 4 hours. A diagram of the assembled feedthrough is shown in Figure 5.3.2.
Figure 5.3.2. Diagram of one of the 16-wire feedthroughs used for our experiments. A tapered stainless steel tube is soldered to a brass flange that attaches to the experimental cell. The wiring is inserted into the Teflon wire alignment array and a Teflon mold is clamped around the stainless steel tube. The Teflon mold is filled with epoxy and the entire assembly is baked at 100° C. The feedthrough is later sealed to the cell flange with an indium o-ring.

The new feedthroughs were attached to the cell and the dilution refrigerator was cooled while the IVC was monitored with the leak detector. Helium gas was purified by running it through a liquid nitrogen cold trap and stored in a gas ballast with a volume of 19.3 liters. Gas from the ballast was allowed to condense until the pressure change in the ballast was 1 Torr. From the ideal gas law, this corresponds to $6.35 \times 10^{19}$ atoms. Using
0.145 g/cm$^3$ for the density of liquid helium, this gives a liquid volume of 2.9x10$^{-3}$ cm$^3$.
This is equivalent to a 1 µm thick layer of helium at the bottom of the cell, so the liquid is
at saturated vapor pressure. The superfluid film thickness $t$ as a function of distance $h$
above the bulk liquid is given by$^7$
\[
t = \left( \frac{\alpha}{mgh} \right)^{1/n}
\]
where $n = 3$ for $t \leq 1$ nm and $n = 4$ for $t >> 25$ nm and $\alpha$ is the van der Waals potential
for the substrate, which in this case is copper. For $h = 2$ cm the helium film thickness is
approximately 30 nm.$^8$ The base temperature reached with helium in the cell is 290 mK.
As shown in Figure 3.1.1, at this temperature the mean free path of helium atoms at
saturated vapor pressure is longer than the dimensions of the experimental cell, so we
should be able to use the beam sources and detectors to study helium atom beams
traveling ballistically through a vacuum under these conditions.

5.4. Experimental Results

For the first experiments we sent electrical heating pulses through one of the three
sources using a pulse generator that was capable of sending voltage pulses of variable
widths and also had the ability to ramp the pulses. We found that we could detect a signal
on one of the bolometers from each of the three sources, but one of the bolometers was
not working. There are therefore six possible combinations of source and detector. The
source-detector distances and angle between the source and detector are given in Table 1.
<table>
<thead>
<tr>
<th>Detector Source</th>
<th>Bolometer 1</th>
<th>Bolometer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>RuO₂</td>
<td>TiO₂</td>
</tr>
<tr>
<td>Distance (cm)</td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Angle (degrees)</td>
<td>20.1</td>
<td>40.3</td>
</tr>
</tbody>
</table>

Table 1. Source-Detector distances and angles for the experimental cell shown in Figure 5.3.1. Bolometer 1 is a 20 nm thick Ti film sputtered onto a 2.5 mm diameter, 0.5 mm thick sapphire substrate. Bolometer 2 is a 20 nm thick Ti film sputtered onto a 1.5 mm diameter, 0.9 mm thick sapphire substrate. The RuO₂ source is a commercial thermometer, while the Cr and TiO₂ sources are approximately 40 nm thick films deposited by thermal evaporation onto 2.5 mm diameter, 0.5 mm thick sapphire substrates.

Mulders and Wyatt⁶ had previously demonstrated that beams with narrow velocity distributions could be more easily generated by using a ramped beam pulse. We observed the same effect, as demonstrated in Figure 5.4.1. The beams shown in Figure 5.4.1 were created by sending a square or ramped pulse through the Cr heater and detecting the beams using bolometer 2. When beams created with the same pulses are detected on bolometer 1, which is at an angle of 39.3° with respect to the source, the results are very different (Figure 5.4.2). In this case both beams are very broad and ramping the pulse makes very little difference. This is most likely due to a lower evaporation rate at this angle, which would cause less cooling from collisions in the beam. This is supported by the fact that the signal intensity observed at this angle is much lower, although it is also possible that bolometer 1 is less sensitive than bolometer 2.
Figure 5.4.1. Comparison of helium atom beams created with a square pulse and a ramped pulse. The points show the voltage pulse sent to the heater for the square pulse and the detected signal, while the lines show the ramped voltage pulse followed by the signal detected from that pulse. The source is the Cr heater and the detector is bolometer 2. From Table 1 the source-detector distance is 4.7 cm and the angle is only 3°. The power input to the heater is 1.37 mW.
Figure 5.4.2. Comparison of helium atom beams created with a square pulse and a ramped pulse. The points show the voltage pulse sent to the heater for the square pulse and the detected signal, while the lines show the ramped voltage pulse followed by the signal detected from that pulse. The source is the Cr heater and the detector is bolometer 1. From Table 1 the source-detector distance is 3.2 cm and the angle is 39.3°. The noise is due to the lower intensity signal observed on this detector. The power input to the heater is 1.37 mW.

It is clear from Figure 5.4.1 that the pulse shape has a significant effect on the beam shape. This may be due to the importance of collisions in determining the final beam shape. If the source is heated quickly to a low temperature, it will begin to emit slow-moving atoms with an average velocity determined by the source temperature. If at some later time the source is heated to a higher temperature by increasing the power input, the source will emit atoms with a higher average velocity. The higher velocity atoms would eventually catch up to the low velocity atoms and they will collide. After these collisions
the high and low velocity atoms would tend towards the same velocity. The end result is a much more narrow beam with a lower internal temperature. This is essentially the same effect as that observed in supersonic expansions, but we take advantage of our ability to create atoms of different velocities at different times to enhance the cooling effect.

To further test this effect, we obtained a National Instruments PCI-MIO-16E-1 Multifunction Input/Output card that was capable of converting an arbitrary digital array into an analog output voltage. The voltage resolution is 12 bits and the maximum update frequency is 1.25 MHz. The card was sent an array of voltages that were calculated according to the equation

\[ V = \frac{t^n}{c} \]  

(5.11)

where \( t \) is time and \( c \) and \( n \) are constants that were determined by the desired maximum power input to the source. For a given maximum input power, \( n \) was varied until the narrowest possible signal was observed on bolometer 2. The narrowest signals were observed for \( n=0.7 \) and \( n=0.8 \) depending on the power levels used, as shown in Figure 5.4.3.
Figure 5.4.3. Comparison of beam shape as the input pulse shape is changed. The beam shape is given by equation (5.11) where \( n \) is varied from 0.6 to 0.8. The results for \( n=0.7 \) and \( n=0.8 \) are very similar and give the narrowest beam shape we observed, while \( n=0.6 \) and lower tend to broaden the beam shape. The source pulse shown for \( n=0.8 \) is also shown. The source pulses for \( n=0.7 \) and \( n=0.6 \) start and end at exactly the same time as the pulse shown.

We observed that \( n=0.7 \) gave consistently narrow beams so this was used as the pulse shape as other properties of the input pulse were changed. We then input pulses with lengths from 50 µs to 200 µs with a maximum input power for each pulse of 2.7 mW (Figure 5.4.4.) The beam shapes for the 50 µs and 100 µs pulses are almost identical, whereas the 200 µs pulse gives a much wider beam. This is most likely due to the fact that the beam itself is created over a longer period of time. The similarity of the two shorter pulses may indicate that collisions in the beam cause the velocity distribution to
narrow and that these beams reach approximately the same temperature. The beam from the longest pulse may also have the same velocity distribution, but the difference in initial evaporation time between atoms evaporated at the beginning of the pulse and atoms evaporated at the end of the pulse causes the observed time of flight distribution to broaden.

Figure 5.4.4. Comparison of beam shape as the input pulse length is varied from 50 µs to 200 µs. The beam shape is given by equation (5.11) with \( n = 0.7 \). The detected beam width changes very little from 50 µs to 100 µs, while at 200 µs the width is much greater.

Since we are interested in finding the conditions under which the narrowest beams can be created, we then varied the pulse power under the conditions that have so far created the narrowest beams. Figure 5.4.5 shows the detected signal for 50 µs long pulses described
by equation (5.11) with $n = 0.7$. The maximum pulse power ranges from 2.5 mW to 890 $\mu$W. All of the detected beams have approximately the same width but the average velocity increases with increasing pulse power, as expected from equation (5.4).

Figure 5.4.5. Comparison of beam shape as the input pulse power is changed. The input pulse length is 50 $\mu$s. The beam shape is given by equation (5.11) with $n=0.7$. The leftmost detected beam is due to the highest maximum input power of 2.47 mW. As the detected beam moves to the right the power inputs are 2.0 mW, 1.65 mW, 1.39 mW, 1.18 mW, 1.02 mW, and 0.89 mW respectively. As the power input is decreased, the average beam energy decreases.

Up to this point our data is consistent with that reported by Meyer et. al. and Mulders and Wyatt. The maximum input pulse power reported in either of these papers is 2.5 mW. At this power, Mulders and Wyatt report that the average beam energy was 3.1 K, which
agrees with our results. However, we found that when the maximum pulse power is increased above 2.5 mW, the observed beam shape changes drastically. As shown in Figure 5.4.6, at a power level of 3.13 mW, a slight bulge appears on the right side of the peak. At 4.09 mW, a second peak appears to the right of the first one. At 5.56 mW, the second peak increases in magnitude relative to the first peak and becomes even sharper. As shown in Figure 5.4.7, when the maximum pulse power is increased to 9.89 mW, a third peak appears, once again at lower energy than the other peaks. Figure 5.4.8 shows the results as the maximum power input is increased above 10 mW and up to 16.35 mW. Three peaks continue to be observed, but the first peak decreases in magnitude with respect the second and third peaks until the maximum intensity is observed on the third peak at the highest power level shown.
Figure 5.4.6. Comparison of beam shape as the input pulse power is increased. The input pulse length is 50 µs. The beam shape is given by equation (5.11) with n=0.7. As the maximum input pulse power is increased above 2.5 mW, we begin to see two separate peaks. This is not consistent with the theory of collisional narrowing presented in section 5.2.
Figure 5.4.7. Comparison of beam shape as the input pulse power is increased. The input pulse length is 50 µs. The beam shape is given by equation (5.11) with \( n=0.7 \). As the maximum input pulse power is increased to 10 mW, we begin to see three separate peaks.
Figure 5.4.8. Comparison of beam shape as the input pulse power is increased. The input pulse length is 50 μs. The beam shape is given by equation (5.11) with n=0.7. As the maximum input pulse power is increased above 10 mW, the first peak decreases in magnitude relative to the second and third peaks.

Observation of more than one peak when the input pulse power is increased is inconsistent with the interpretation of the ultra-cold beams as supersonic expansions from a thin film of helium. If this interpretation were correct, higher pulse powers would be expected to generate higher beam densities, which in turn would be expected to increase the narrowing of the beam due to collisions. If more than one peak is observed it is not possible that the beam is in thermal equilibrium at any point as it expands away from the source. If the beam is not in internal thermal equilibrium then the theory describing a supersonic expansion cannot be applied.
5.5. Discussion

We have demonstrated the ability to create ultra-cold helium atom beams with narrow velocity distributions. We have essentially reproduced the results of references 4 and 6 for conditions similar to the ones used in their experiments. We have also found that increasing the maximum heater input pulse power beyond that used by either of these workers generates helium atom beams with more than one peak in the distribution. There are a number of possible interpretations of these peaks. One possibility is that we are somehow heating other parts of the cell besides the Cr film source and helium is being evaporated from another source when the pulse is sent to the heater. Since everything else in the cell besides the other heaters is firmly anchored to the cell, this is very unlikely. Another possibility is that clusters of helium atoms are being evaporated and they travel more slowly than single atoms. If this were the case we would expect an extremely broad time of flight distribution due to the wide range of cluster masses produced. We would also expect that the clusters would move more slowly, so the new peaks should appear at a much later time. This is not observed, so cluster formation is unlikely. It is also possible that the original interpretation of these beams as ultrasonic expansions is incorrect and the narrow velocity distributions reflect the distribution of quasiparticles in the liquid that evaporates helium atoms.

Quantum evaporation from thin films of superfluid helium has never been observed. It has been studied in great detail in the bulk liquid. In general, a narrow peak in the time of flight spectrum is observed due to atoms that have been evaporated by phonons and a
broad peak is observed due to atoms evaporated by rotons. The phonon peak is due to atoms with average energy of about 3.3 K. The narrow range of energies observed from quantum evaporation by phonons was explained as being due to spontaneous decay of phonons with energies less than 10 K in the liquid. The rotons appear with a range of energies. Some of the atoms evaporated by rotons appear earlier in the time of flight spectrum, while a greater number of atoms evaporated by rotons appear later in the spectrum. It is difficult to determine the exact range of energies because the rotons travel with a number of different velocities in the liquid as well as the vacuum. It was clearly shown that these separate peaks were due to quantum evaporation of atoms by quasiparticles from two distinct regions of the excitation spectrum. (see Figure 5.5.1.)

![Figure 5.5.1. Excitation spectrum of superfluid helium. Excitations on the left side of the excitation spectrum are called phonons and excitations near the minimum of the curve in the middle of the spectrum are called rotons. The shaded region represents the range of energies of the beams that we have observed in our experiments.](image)
In our experiments we observe only a single peak in the time of flight spectrum for low energy input pulses. As the power level input to the source is increased two peaks appear, and then at the highest power we see three peaks. In order to try and understand this in terms of the excitation spectrum of the superfluid, it is helpful to look at the signal as a function of the kinetic energy of the detected atoms. In Figure 5.5.2 we see that for input pulse powers from 0.89 mW to 2.47 mW only one peak is observed with an average kinetic energy that increases from 2.6 K to 3.1 K. In all of the following graphs the energy is calculated assuming all atoms are evaporated at the beginning of the pulse. If later evaporation times are assumed, the calculated energies of the beams will increase. According to the excitation spectrum shown in Figure 5.5.1, there are two types of excitations in this energy range. These are rotons and high energy phonons. As shown in previous quantum evaporation experiments using bulk liquid, phonons with energy less than 10 K have very short lifetimes because they can spontaneously decay. This would explain why there is very little signal due to lower energy phonons. Phonons of energy greater than 10 K will evaporate atoms with kinetic energy greater than 3 K.
Figure 5.5.2. Helium atom beam signal as a function of the kinetic energy of the detected helium atoms calculated from the time of flight spectrum. For the input pulse powers shown here, only one peak is observed, centered at about 3 K.

Figure 5.5.3 shows the detected signal as the input energy is increased above 2.5 mW. Here we begin to see a peak centered at a much higher energy. The average energy of the high energy peak increases with increasing input power, but the peak centered at 3 K remains. This is qualitatively what one would expect due to excitations from superfluid helium. The peak centered at 3 K represents stable phonons with an energy of 10 K or more in the liquid, while the higher energy peak represents very high energy phonons whose intensity increases due to the increase in density of states at 14 K. Figure 5.5.4 and Figure 5.5.5 show the development of the third peak at approximately 2 K. This low energy peak would represent rotons with an average energy of about 9 K. However, it is
difficult to model the interactions between the particles in the liquid, so further study is needed to confirm whether or not these peaks are due to quantum evaporation, and to determine why this occurs only at high input pulse powers.

Figure 5.5.3. Helium atom beam signal as a function of the kinetic energy of the detected helium atoms calculated from the time of flight spectrum. As the input pulse power is increased, a second peak appears at about 5 K.
Figure 5.5.4. Helium atom beam signal as a function of the kinetic energy of the detected helium atoms calculated from the time of flight spectrum. As the input pulse power is increased further, a third peak appears at about 2 K and the average energy of the highest energy peak increases to above 5 K. The central peak remains at 3 K.
Figure 5.5.5. Helium atom beam signal as a function of the kinetic energy of the detected helium atoms calculated from the time of flight spectrum. At the highest input pulse powers, we see three peaks, one centered at 2 K, another at 3 K, and the highest energy peak is centered around 5.5 K.

5.6. Conclusion

We have demonstrated the ability to produce ultra-cold helium atom beams by evaporation of superfluid helium from thin metal films. Our data at low input pulse power is consistent with previous data by other workers. The earlier work indicated that the narrow beams were due to collisional beam cooling similar to that which occurs in a supersonic expansion. To our knowledge, there are no previous reports of helium atom
beams created with input pulse powers higher than 2.5 mW. Our data for this input power may be inconsistent with the interpretation of these beams as supersonic expansions, but further study is needed to confirm this. In any case, the beams created at low powers will be sufficient for study of the condensate-mediated and ballistic roton processes discussed in Chapter 1.

6. Conclusions

We have developed all of the experimental techniques necessary to study the condensate-mediated and ballistic roton processes in superfluid helium. During the course of this development, we have made several interesting discoveries involving the wetting of superfluid helium on cesium-coated surfaces and the production of ultra-cold helium atom beams. We have demonstrated a technique for creating a freestanding layer of superfluid helium that will be very valuable for future studies of processes in bulk helium. We have demonstrated for the first time the use of titanium bolometers for the study of helium beams. This is significant because previous studies of helium beams at these temperatures have used semiconductor bolometers, which have a long time constant, or zinc bolometers, which require that a large magnetic field be applied parallel to the surface of the superconducting film.

We have also studied helium atom beams created with pulse powers higher than has ever been reported. The helium atom beams change character significantly in this regime, and these results will ultimately enable a better understanding of the processes that govern the evaporation of helium atoms from thin films. These results must be studied in greater detail to understand the processes involved. There are a number of parameters that can be adjusted to test the conditions under which the helium atom beams change shape and develop multiple peaks in the time of flight spectrum. The beams should be studied as a function of angle with respect to the plane of the source. The helium film thickness can be varied by introducing less helium gas into the experimental cell. The resulting beams
should be tested as a function of distance away from the source as well. Finally, all of the
input pulse shapes and power can be varied for each of the configurations mentioned
above. It would also be interesting to study the beams as the cell temperature, and
therefore the initial helium film temperature, is lowered down to 100 mK, at which
temperature very few rotons are present in the film.

In order to perform the condensate transmission process, the superfluid suspension
apparatus described in Chapter 2 must be designed and built for the experimental cell we
have used in the helium atom beam experiments discussed in Chapter 5. This cell was
designed with these changes in mind. A small 1” diameter inner can must be built so that
it seals directly to the top flange of the cell with an indium o-ring, as shown in Figure 6.1.
A platinum aperture such as the one described in Chapter 2 must be inserted into the
bottom of this can. The same coaxial capacitors that were used in the original suspension
experiment can be attached directly to the inside of this can to measure the superfluid
helium level. Three separate coaxial cables must be installed from the top of the cryostat
down into the cell so that the helium level can be measured using a capacitance bridge.
Finally, an electrical feedthrough must be designed for the cell that will allow a current of
7 A to flow with very little resistance. Clearly such a high conductivity wire cannot be
attached to the cell and connect to the top of the cryostat under normal dilution
refrigerator operating conditions due to the large heat leak involved. However, a
removable connector can be put directly on the cell and the cryostat can be cooled to
liquid nitrogen temperature without using the vacuum can. The cesium evaporators can
be installed in the cell and evaporation will take place with the cell held at 77 K. The
cryostat can then be warmed to room temperature, removed from the dewar, and then the high current wire can be disconnected from the cell. The vacuum can will then be installed and the cryostat will be cooled down in the manner described in Chapter 3. The suspension experiment can be reproduced at lower temperature using the dilution refrigerator. When the helium has been suspended, helium atom beams will be created using the methods described in Chapter 5 and the signal will be detected on the other side of the slab using the bolometers described in Chapter 4.
In order to detect the ballistic roton process, the experimental cell must be cooled to below 100 mK with helium in the cell. Currently we can only cool the cell down to 290 mK after helium has been introduced into it. We expect that this is due to a heat leak from superfluid film flow. Since superfluid flows towards warmer areas, the helium in the cell will climb up the walls of the capillaries until it reaches a point at which it is no
longer superfluid. At this point it has a fairly high vapor pressure and it will evaporate and then condense when it reaches an area of the cell that is at a lower temperature. This represents a very large heat leak, which can only be eliminated by using much smaller capillaries to restrict the surface area along which the superfluid film moves. It is also beneficial to increase the length of the capillaries between each stage of the refrigerator. These modifications should be made to the cryostat before attempting to observe the condensate-mediated process. When the refrigerator can be cooled to below 100 mK with bulk helium in the cell, the condensate transmission experiment should be performed at 100 mK and 300 mK. If there is a signal due to the ballistic roton process at 100 mK, it should go away when the experiment is performed at 300 mK and the remaining signal will be due to condensate mediated transmission through the suspended slab of superfluid helium. We also expect to see a signal on our detectors due to the condensate mediated process approximately 10 µs earlier than a signal due to the ballistic roton process for a slab thickness of 2 mm.