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DEPARTMENT OF PHYSICS

ONE DIMENSIONAL BEHAVIOR OF SUPERFLUID HELIUM

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ABSTRACT

In truly one-dimensional systems, superconductivity and superfluidity are destroyed at any non-zero temperature due to phase fluctuations. This 1D confinement effect in superconductors has been studied through the behavior of metal nanowires. Here we report the results of analogous experimental studies of superfluidity in quasi-one dimensional geometries realized with glass fibers with long and narrow open channels. The flow of liquid helium through glass fibers at temperatures below 4 K was measured with a quartz crystal microbalance and a mass spectrometer. An abrupt increase of the flow rate at low temperatures was observed in two glass fibers of 1 m length – 1.7 μm diameter and 4 cm length – 150 nm diameters respectively. This preliminary result suggests the existence of superfluidity in quasi-1D systems with aspect ratio as high as 6×10^5. The effects of the 1D confinement will be discussed.

TABLE OF CONTENTS

LIST OF FIGURES

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Chapter 1

Helium

Helium is a unique element in that it exhibits many phases and therefore many properties. It is an inert gas and is the second most abundant element in our universe. However, here on earth, it is scarce and it is extensively recycled. Helium naturally exists in the gas phase. However, under extreme conditions of low temperatures and high pressures; it can be a normal fluid, superfluid, and solid as seen in Figure 1. The superfluid transition temperature, under atmospheric pressure, of ^{4}He, called the lambda point, is 2.17K. Superfluidity is a quantum phenomena and the subject of this study.

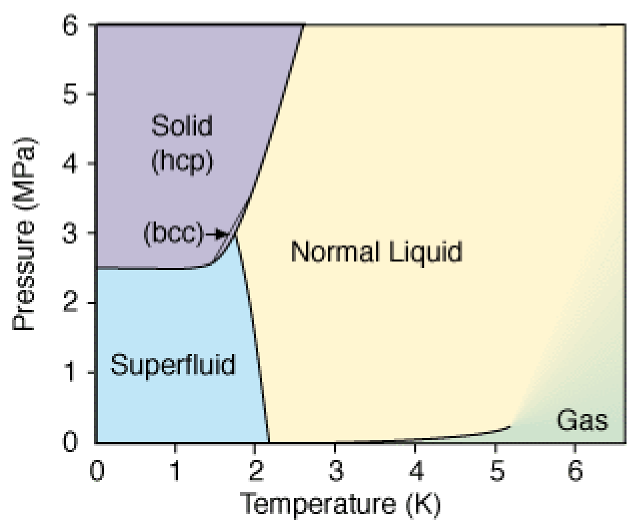

Figure 1: Helium phase diagram [1]

1.1 Theory and Background

Our world is governed by quantum mechanics [2]. In situations corresponding to everyday life, quantum mechanics reduces approximately to classical mechanics. Quantum mechanics becomes distinctive for describing the behavior of sub-microscopic particles. The basic tenet of quantum mechanics is the particle-wave duality of matter. Particles such as tennis balls and electrons have wave-like characteristics with the De Broglie wavelength defined as the ratio of Planck's constant (a fundamental constant of nature with units of angular momentum and with a very small magnitude, 6.6×10^{-34} Js) to the particle momentum. For everyday objects, such as a tennis ball, the wavelength is miniscule and the wave-like properties do not manifest themselves. In contrast, for an electron or even for a helium atom, the wavelength can become measurably large. The quantum properties become measurable when the wavelength becomes comparable to other characteristic length scales in the problem. For example, liquid helium at very low temperatures behaves quantum mechanically because the De Broglie wavelength of a helium atom becomes comparable to the inter-particle spacing.

There is a second fundamental point about all particles. Particles are endowed with a quantum number called spin, which describes its wave function. Integer spin particles are Bosons whereas odd integer multiples of ½ spin (1/2, 3/2, 5/2 ….) are called Fermions. These two classes of particles behave distinctly. When two indistinguishable particles are interchanged, the square of the absolute value of the wave function must be preserved. This is an observable quantity that provides a direct measure of the likelihood of finding a particle at a given location. But this preservation can happen in at least two ways: the wave function remains the same in sign and magnitude or the wave function remains the same in magnitude but flips the sign. The former corresponds to Bosons and the latter to Fermions. More generally, one may consider a generalized concept of anyons – the wave function changes by $e^{i\varphi}$, where φ is real. Bosons have

$\varphi = 0$ and Fermions $\varphi = \pi$.

Remarkably, the statistics associated with Bosons and Fermions are completely different. Two or more Bosons can in principle occupy the same level. In contrast, a given energy level for a Fermi system can be occupied by no more than a single Fermion with a particular set of quantum numbers. Bosons obey Bose-Einstein statistics whereas Fermions obey Fermi-Dirac statistics. Strikingly, distinguishable particles (every day classical particles) obey Boltzmann statistics.

Satyendra Nath Bose pointed out that the statistics are distinct for classical distinguishable particles and quantum indistinguishable particles. Imagine tossing two coins and studying the outcome. There are four possibilities: the first and second coins come up HH, HT, TH, and TT respectively. Thus the probability of 2 Heads is ¼, 2 Tails is ¼, and a Head and a Tail is ½. This is the classical situation underlying Boltzmann statistics. For quantum coins, which are indistinguishable, there is no distinction between coin 1 and coin 2. In this case, the probability of 2 Heads, 2 Tails, and 1 Head and 1 Tail are each equal to 1/3. This bizarre result along with the possibility of multiple particles residing in a given energy level leads to Bosons (integer spin indistinguishable particles) obeying Bose-Einstein statistics. A stunning prediction of Einstein was the phenomenon called Bose-Einstein condensation (BEC), which results, at sufficiently low temperatures, in a macroscopic occupation of the ground state. The Bosons behave coherently in this state. They exhibit collective behavior with an energy gap – a minimum energy is needed to remove this coherence – and the behavior is stable.

1.2 Nobel Prize winning experiments and theory on Bose-Einstein Condensation

Experiments have confirmed the existence of a Bose-Einstein Condensate (BEC). Numerous Nobel Prizes have been awarded to experiments and theory developed for BECs [3]. The two main realms cover superconductivity and superfluidity.

The first Nobel Prize on the subject was awarded in 1913 to Kamerlingh Onnes for his discovery of superconductivity. Onnes was able to observe superconductivity because of a major technological innovation. He was the first to devise a method to liquefy Helium and cool it to around 0.9°K which was the closest to absolute zero that anyone had been able to reach. He noted the peculiar properties of helium - the density of the liquid had a maximum at 2.2 °K which was later found to be the lambda point of Helium. Ordinary fluid helium is called He I and superfluid helium (which has undergone BEC) is called He II. Onnes observed superconductivity in mercury, tin, and lead at these low temperatures and he noted that the current was persistent. Onnes wrote in his Nobel lecture about his experiments of the electrical properties of mercury:

> *"As has been said, the experiment left no doubt that, as far as accuracy of measurement went, the resistance disappeared. At the same time, however, something unexpected occurred. The disappearance did not take place gradually but abruptly. From 1/500 the resistance at 4.2°K drops to a millionth part. At the lowest temperature, 1.5°K, it could be established that the resistance had become less than a thousand-millionth part of that at normal temperature. Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity."*

This seminal discovery of superconductivity led to a major puzzle. Electrons are Fermions – so how could BEC be implicated as an explanation of superconductivity? The answer would come decades later.

In 1978, Pyotr Kapitza won the Nobel Prize for developing a new method of cooling down to millikelvin temperatures by using turbines. He then began to do careful experiments with Helium and discovered superfluidity in 1939. He measured the laminar viscosity of He II to be "at least 1500 times smaller than" the viscosity of He I. Allen and Meisner also observed and measured the effects at the same time as Kapitza but they are not granted as much credit as him. Lev Landau in 1962 won the Nobel Prize for developing a theory for superfluid helium based on a two fluid model. He proposed that novel excitations were the cause of the unique properties of Helium and that the superfluid must be made up of two types of superfluids: He I and II. He studied the collective effects in superfluid helium and postulated excitations similar to phonons but with a different dispersion relationship. The energy of these excitations increases with momentum near the origin but shows a maximum and then a minimum and rises again. The excitations with small momentum are the usual phonons while those in the vicinity of the energy minimum are called rotons. Landau also predicted novel second sound wave propagation in superfluid helium. All these predictions have been confirmed experimentally.

In 1972, Bardeen, Cooper, and Schrieffer won the Nobel Prize for developing a complete microscopic theory of superconductivity and showed that it was caused by "coupling of electrons to the vibrations of the crystal lattice" [4]. The basic contribution of Cooper was to show that the lattice vibrations can mediate the coupling between two electrons (which normally repel because of like charges) to become attractive leading to electron pairing. Thus the electrons behave like pairs in a ballroom dance, not necessarily dancing in close spatial proximity to each other, and become Bosons because they now have integer spin. The condensation of these Bosons through the mechanism of BEC then results in superconductivity. The coherent dance of these paired electrons requires a threshold energy to disrupt leading to a stable low temperature superconducting phase.

Georg Bednorz and Alex Müller in 1987 won the Nobel Prize for discovering a new class of superconductors in ceramic materials with a higher critical temperature than had been observed previously. This began a revolution and labs around the world reported discoveries in novel materials with higher and higher critical temperatures. The significance of a high temperature superconductor is that its exceptional electrical properties ought to be useful in applications at relatively high temperatures with cooling provided by the much cheaper liquid nitrogen than liquid helium. The mechanism of pairing in high temperature superconductors remains unresolved. Recent optical spectroscopy measurements [5] on $Bi_2Sr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ crystals with simultaneous time and frequency resolution have attempted to disentangle the phonon and electron contributions to pairing. The basis for the interpretation is the relative rapid temporal response of the electronic excitations compared to that of the phonons. The authors find that electrons mediate the pairing rather than the phonons strongly suggesting that conventional Cooper pairing is not the operative mechanism for that material. This work shows that the pairing mechanism in high temperature superconductors may be distinct from ordinary phonon-mediated electron pairing.

In 1996, the Nobel Prize was awarded to David M. Lee, Douglas D. Osheroff, and Robert C. Richardson for the discovery of superfluid helium 3. Helium 4 with two protons, two neutrons, and two electrons and has an even number of constituent particles and is therefore a boson. In comparison ^3He has only 1 neutron and has an odd number of particles and is therefore a fermion. A fermion cannot condense into a BEC. However, following the ideas expounded in the BCS theory, a fermion can pair with another fermion and then it will act as a boson and condense at an extremely low temperature. Therefore ^3He atoms can pair and become a BEC at a thousandth of a degree. The lambda temperature for ^3He is many times smaller than that of ^4He. There are two reasons for this. Just as in a superconductor, but through a different mechanism, the pairing of two atoms of ^3He occurs at a low temperature and the Bose condensation at an even lower temperature. Also, the mass of a pair of ^{3}He atoms is larger than a single ^{4}He atom and of course much larger than the bare mass of an electron pair.

Cornell, Ketterle, and Weiman were awarded the Nobel Prize in 2001 for observing BEC of Alkali gas atoms. This is a much simpler system than the condensed matter systems of superconductors and superfluids. The basic idea is to take away the confining magnetic fields holding the atoms undergoing BEC within a trap and photographing the density distribution after a fixed time has elapsed [6]. In Figure 2, the picture on the left shows the situation at a temperature higher than the condensation transition temperature. The picture on the right shows that the BEC, which is a collective peak at the center has hardly moved during the time interval vividly confirming the existence of the BEC. Laser cooling first cools the alkali gas and then it is put into a magnetic trap and evaporative cooling, cools it to the nano-Kelvin range.

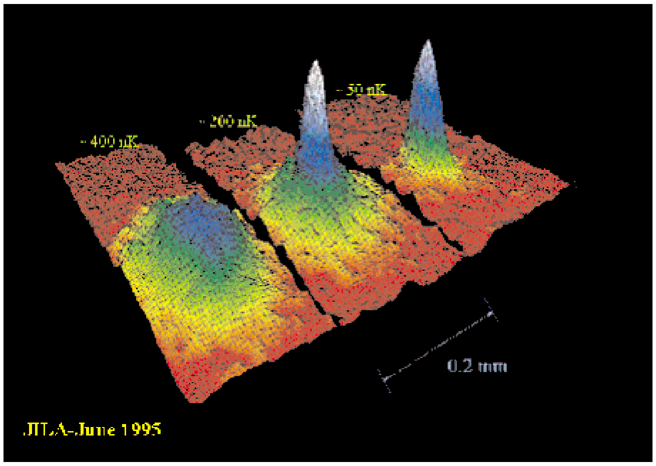

Figure 2: Density Distribution [6]

Three density distributions of the expanded clouds of rubidium atoms at three different temperatures. The appearance of the condensate is apparent as the narrow feature in the middle image. On the far right, nearly all the atoms in the sample are in the condensate. The original experimental data is a two-dimensional black and white shadow image, but these images have been converted to three dimensions and given false color density contours.

In 2003 the Nobel Prize was awarded to Alexei A. Abrikosov, Vitaly L. Ginzburg, and Anthony J. Leggett for their theoretical studies of superconductors and superfluid helium 3.

1.3 Recent Experiments studying Superfliud flow

Superfluidity and superconductivity provide vivid manifestations of the quantum world at macroscopic scales [2] [7], especially through the Josephson effect. The canonical Josephson effect arises at a junction of two weakly coupled superconductors separated by a thin layer of insulator that allows for tunneling of electron pairs from one side to the other. Because superfluidity in quantum fluids is an analogous phenomenon to superconductivity, it is thought that Helium 4 can also exhibit the Josephson effect, which could lead to the development of novel quantum interference devices.

The Josephson effect was first observed with ^3He. ^3He has a higher healing length than ^4He, which lends itself to an easier experimental technique. As discussed by Sato and Packard in a recent review [8], the aperture needed to measure the effect in ^4He was thought to be too fragile and, furthermore, the technology to study mass current is not currently available. Therefore arrays were used instead of apertures, which led researchers to question the feasibility of using apertures and whether they would compromise quantum coherence.

Previous studies have shown the existence of the Josephson effect in ^3He and recent studies have claimed to observe it in ^4He. In 1988, Avenel and Varoquaux [9] published the results of a careful study of the Josephson effect and quantum phase slippage in superfluids in Physical Review Letters. They clearly observed the Josephson effect in ^3He but were unable to observe the Josephson effect in ^4He. They did observe phase slips in ^4He, which, as noted by them, are precursors to the Josephson effect.

In 2001, Sukhatme et al. [10] reported the observation of the Josephson effect in ^4He in the journal Nature. Their paper pointed out that it still remained an open question as to why fluctuations do not inhibit the Josephson effect. However, to counter this puzzle, they supported their observations by reporting the results of computer simulations, which were in accord with their experimental results. Motivated by this work, four years later, Hoskison et.al [11] reported, in Nature, experimental confirmation of Sukhatme et al.'s result. This paper provided the first unambiguous evidence of the existence of the Josephson effect in ^{4}He, opening the way for further studies of the fundamental physics underlying the phenomenon and the development of numerous potential applications. Since then, additional experiments have been carried out to explore other driving forces of the Josephson oscillations including pressure [12] and thermal energy [13]. At this point, one can confidently state that superfluid ^{4}He exhibits the Josephson effect.

Superfluid interferometry which uses the Josephson effect provides a setting of very low temperatures, precision nanoscale fabrication, carefully designed electronics, and the imaginative use of computers for running the experiments. The exploration of the Josephson effect in superfluid ^{4}He will have many applications in condensed matter physics and beyond [9] [8]. The stage is set for a study of these and other novel effects of the macroscopic manifestations of quantum mechanics.

Chapter 2

Dimensionality and superfluidity

We will briefly review theoretical ideas pertaining to phase transitions [14] in general and superfluidity in particular. The idea behind a continuous phase transition is most simply explained within the context of a classical Ising model. This model approximates the behavior of a magnet. It consists of objects, that we will call spins, which can point up or down. Quite remarkable behavior ensues when one takes a set of spins on a lattice, for simplicity, and couples the nearest neighbors. The coupling can be thought of some kind of peer pressure: the energy is lower if a spin aligns with a neighbor rather than anti-align. The difference in energy between these two relative orientations sets an energy scale that one conventionally calls 2J: when a pair of spins is parallel, their energy of interaction is –J and the pair is happy; when they are anti-parallel, the interaction energy is +J. The behavior of a group of N such interacting spins can be studied as a function of temperature. One sums over the Boltzmann factor for all the (2^N, for N spins) configurations of the system to obtain the partition function

$$Z = \sum e^{\frac{-E_i}{k_B T}}$$

where E_i is the total energy of the i^{th} configuration, k_B is Boltzmann's constant, and T is the temperature. The free energy is then obtained as

$$F = -k_B T \ln Z$$

and thermodynamic quantities such as the specific heat can be calculated from this.

A quite remarkable phenomenon happens in the limit of N approaching infinity called the thermodynamic limit. Even though the partition function is an analytic function (a sum of simple exponentials), non-analytic behavior (as we shall see later, the magnetization continuously drops to 0 as one increases the temperature to the critical value and stays 0 thereafter and this necessarily leads to discontinuities in derivatives) emerges at a special value of temperature called the critical temperature strictly only in the thermodynamic limit. Note that in the way the problem has been defined, there is perfect symmetry between up and down orientations of the spins - the definition of the problem does not favor up over down or vice versa. The model merely postulates that a parallel configuration of neighboring spins has a lower energy than an antiparallel configuration. The free energy has two components – an internal energy piece and an entropic piece: $F = U - TS$, where U is the internal energy and S is the entropy. At very high temperatures, the entropic term dominates. The largest entropy state is one in which about half the spins are up and the other half are down. Because the temperature is high, the spins are able to point up or down without regard to the orientation of their neighbors and the magnetization (defined as the imbalance between up and down spins) is close to zero. At very low temperatures, all that matters is U and the state of minimum U is obtained when neighboring spins are parallel. This drive for neighboring spins to be parallel results in a spontaneous symmetry breaking between up and down – the need for all spins to be parallel to each other causes them to be all up *or* all down.

The remarkable feature of this symmetry breaking transition is that it occurs at a non-zero temperature, the critical temperature T_c. Above the transition temperature, the magnetization is zero and it rises continuously from zero below T_c. The behavior of a function that goes down continuously to zero and then stays zero is necessarily non-analytic. When N is not infinity, the transition is rounded and the behavior is not singular.

The spectacular aspect of continuous transitions is that critical exponents, which are *universal*, mathematically characterize the non-analytic behavior in the vicinity of the critical point. Thus, for example, in an Ising magnet in three dimensions, the magnetization approaches 0 as T approaches T_c from below as t^β where the reduced temperature $t = \frac{T_c - T}{T_c}$ and the critical exponent β ~ 0.3265. Note that the exponent is not a simple rational number like 1 or ½ or ⅓. The exponent is said to be universal because one obtains exactly the same exponent for a variety of experimental systems as this idealized model. For example, consider the boiling of water at 1 atmosphere pressure. Water boils at 100C, the density of liquid water and water vapor are quite distinct and there is a latent heat associated with the boiling. Heat needs to be supplied to the water to convert it from the liquid state to the vapor state without an associated increase in the temperature. Now consider what happens if one repeats this experiment at a higher pressure. The boiling occurs at a higher temperature, the latent heat is lower as also the density difference between the liquid and the vapor state. As one continues to increase the pressure to a critical value, the boiling occurs at a critical temperature, the latent heat goes to zero as does the density difference between the liquid and vapor phases. One then obtains a critical point corresponding to the liquid-vapor phase transition. Quite remarkably, the density difference behaves again as t^β with the very same β ~ 0.3265… Indeed the same set of exponents characterizing the singularities are obtained for a three dimensional Ising model on a simple cubic lattice or a face-centered cubic lattice, a liquid vapor critical point, a binary alloy that is about to order or two fluids that are about to become miscible with each other.

This universal behavior stems from the fact that there are many dominant length scales at a critical point. Many of the simplifications in physics arise because there is often a single length or time scale characterizing a system. A water wave at the beach has a characteristic scale of around a meter and the molecular nature of water does not play a role. Likewise, the interaction of two nearby molecules occurs at the nanometer scale and is not sensitive to whether the water molecules are in a teacup or in a lake. In contrast, water in the vicinity of its critical point consists of droplets of water and bubbles of vapor of a range of sizes – shining light on it makes it appear milky white because all wavelengths are roughly equally scattered. The largest size over which these fluctuations occur is called the correlation length. At a critical point, the correlation length diverges to infinity. This phenomenon of the milky white appearance called critical opalescence underscores the complexity of a critical state. But underlying the complexity is beautiful simplicity – universality arises because the differences in many of the details at the molecular level having to do with the chemistry of the material, the nature of the underlying lattice etc. are irrelevant in determining the long length scale behavior. That is why the exponents are universal.

So what are the quantities that determine the universality class of a system? Careful research over the years has shown that what matters are the dimensionality of space and the symmetry of ordering. The symmetry of ordering of a superfluid is distinct from that described by the up-down symmetry of the Ising model. A clue for the correct model is provided by the nature of the superfluid state – it is a state of quantum coherence characterized by a complex order parameter with a magnitude and a phase. Not surprisingly, the superfluid transition is described a simple classical model called the xy model in which a spin, instead of pointing up or down, is akin to the minute hand of a clock described by a phase angle, φ with respect to say the 12 o' clock direction. The energy of interaction between neighboring spins can be described by a cosine function of the difference in their phase angles – a parallel relative orientation is energetically favorable compared to an antiparallel relative orientation. At the lowest temperature, the energy is minimized by again orienting all the spins parallel to each other. The symmetry is now spontaneously broken because, in order to be parallel, they all have to show the same time – a random fluctuation may pick what this time is.

The model may be extended to study the quantity of interest, the superfluid density, in a straightforward manner. In quantum mechanics, the superfluid velocity is proportional to the phase gradient: $v_s = \frac{\hbar}{m}\nabla\varphi$. A simple prescription for obtaining a measure of the superfluid density is to calculate the free energy change per unit volume on introducing a phase change and equating it to $\frac{1}{2}\rho_s v_s{}^2$. This is most readily implemented by measuring the free energy difference on changing the boundary conditions from periodic to antiperiodic and recognizing that the phase gradient is $\frac{\pi}{L}$, where L is the longitudinal scale across which the boundary conditions are applied. Fisher, Barber, and Jasnow [15] first introduced this prescription for calculating the superfluid density, which they described by the term helicity modulus. The superfluid density in three dimensions goes to zero as t^{υ} with the exponent value of around 0.67 for both the xy model and in experiments.

The focus of our work here is the crucial role of dimensionality. There are two important measures of the dimensions – one termed the upper critical dimension (ucd) and the other the lower critical dimension (lcd). The ucd is the value of the dimensionality at and above which the exponents do not change any more. This limit is called the mean field limit – the number of neighbors is sufficiently large that fluctuations do not play a significant role in affecting the exponent. The lcd is the dimension below which there is no spontaneous symmetry breaking at any non-zero temperature. The fluctuations wipe out the non-zero temperature transition.

The lcd for the xy model is 2. Strikingly, in two dimensions, in spite of a mathematical theorem stating there cannot be any long range order at any non-zero temperature, Kosterlitz and Thouless [16] showed that there is a novel superfluid transition in superfluid thin films in which the superfluid jumps discontinuously at a critical point. Remarkably, the transition is from a low temperature phase characterized by algebraic (not truly long range and therefore not violating the theorem) correlations to a conventional high temperature phase in which the spin-spin correlations decay away exponentially with distance. Physically, the algebraic low temperature phase arises from a binding of vortex-anti-vortex pairs and the Kosterlitz Thouless transition corresponds to the unbinding of these pairs.

In a strictly one-dimensional system, the superfluid density is zero at any non-zero temperature. Note that any changes in the boundary conditions in one dimension can readily be accommodated with a local energy cost in one dimension that is independent of the system size. Thus the free energy cost per unit length goes down as the system size increases and the superfluid density vanishes except at zero temperature.

So how does the behavior of a system cross over from three-dimensional to one-dimensional? The experiments described here aim to study just this issue. The key to understanding this is again by looking at the characteristic length scales in the problem. First, for the superfluid in three dimensions, there is a correlation length, which diverges at the lambda point or at the onset of superfluidity. In the vicinity of the critical point, this length is very large and can be safely ignored in our analysis. A dimensionless ratio pertaining to the tube geometry is its aspect ratio or the ratio of the length to the diameter. Then there is the healing length of the superfluid, which is a measure of the length scale from the fiber wall over which the superfluidity goes away. Thus in a narrow tube-like geometry, there is an inert coating of normal fluid whose thickness is given by the healing length. A crucial dimensionless ratio is the ratio of the healing length to the tube diameter. One might expect that there would be no superfluid flow when this ratio becomes larger than a critical threshold as the system becomes truly one-dimensional.

The goal of our measurements will be to carry out careful studies of the onset of superfluidity, if any, in a tube geometry. The variables that can be controlled are the temperature, which in turn controls the correlation length, the healing length which depends on the tube material and the temperature, and the diameter and length of the tube. For narrow tubes in which the constriction becomes smaller than the healing length, one will not be able to detect any superfluid flow – the tube opening may appear pinched off.

Chapter 3

Experimental Setup

The experimental setup up consists of 3 main components: a glass fiber which approximates the one dimensional system, the measuring device of the Quartz Crystal Microbalance (QCM) connected to a mass spectrometer, and the cryostat which cools the system to low temperatures.

3. 1 Glass Fiber

The glass fiber is an optical fiber made by the collaborative team of the Penn State Chemistry group led by John Badding and the ORC (Optoelectronics Research Centre) group in the University of Southampton. The fibers are microstructured optical fibers - the microstructure of the fiber guides the light rather than through conventional total internal reflection. The fiber, as shown in figure 3, is made of silica glass. The fiber is made by stretching the silica glass to make it long. By using a TEM (tunneling electron microscope), one can verify that the fiber is uniformly open. To make a narrower fiber, a high pressure CVD (chemical vapor deposition) technique is employed. Experiments were carried out using fibers of diameters 1.7 µm, 150 nm, and 70 nm.

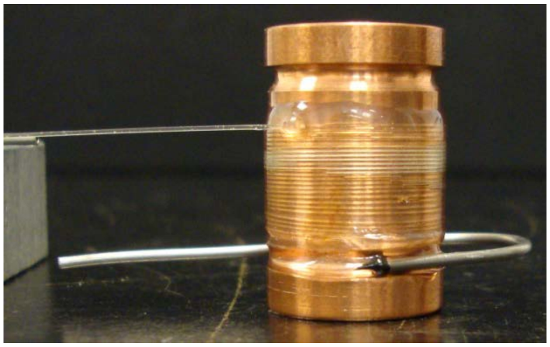

Figure 3: Glass fiber wound on a copper spool

3. 2 Quartz Crystal Microbalance

A quartz crystal microbalance allows one to measure small changes in mass based on the interplay between the elastic and electrical properties of a piezoelectric crystal. Quartz is a piezoelectric material – the mechanical stress of the quartz causes charge to accumulate on its surface. This is because the added pressure induces a voltage drop. The converse holds as well with changes in the stress causing electrical signals. Metal electrodes are attached to the quartz crystal to convey the electrical signal. The QCM is a powerful tool in many scientific and industrial applications.

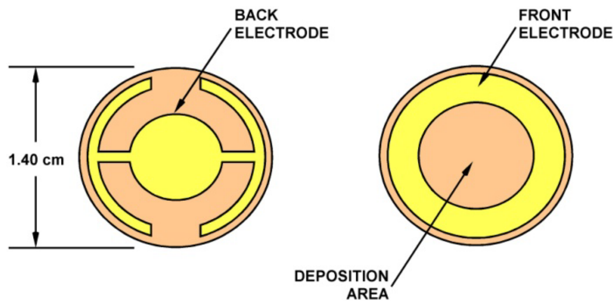

Figure 4: QCM Diagram [17]

The QCM is only made of a few principal parts (figure 4). These include the quartz crystal, metal electrodes, and connecting leads to carry current from the microbalance for the purposes of readout of the results.

The QCM, as seen in figure 4, consists of a thin plate of a single crystal of quartz typically grown from a seed. The crystal is cut carefully in order to minimize the sensitivity of the system to small changes in the temperature of the environment. The quartz crystal is a piezoelectric material - there is a relationship between the elastic and electric properties of the crystal. This special coupling between the elastic and electrical properties, which is the basis of the QCM, arises because the crystalline structure lacks inversion symmetry. In other words, the arrangement of atoms is such that the center of charge is at a different location than the center of mass in the crystalline state of quartz. When an alternating current is passed through a quartz crystal, it vibrates at a specific frequency. The so-called Q-factor of the quartz crystal is very high - the frequency of oscillation is very precisely defined – a key factor for the operation of the QCM. The frequency for resonance and the Q-factor are specific to each quartz crystal. The most commonly used QCM has a resonance frequency of 5MHz, corresponding to 5,000,000 vibrations every second. The high Q is again relevant because small changes in the frequency lead to very precise changes in the electrical current, which can be measured using standard electronics. The microbalance has a resonance frequency of 5MHz. The quartz crystal microbalance was connected to a mass spectrometer, which was a sensitive detector of any flow.

3.3 Cryogenics

A cryogenic system uses cryogenic liquids such as helium and nitrogen to reach low temperatures. Helium and Nitrogen with boiling points of 4.2 K and 77 K respectively are the most commonly used cryogenic liquids. Helium is used to cool systems to below 4 K. A dilution refrigerator, which uses mixtures of the isotopes of helium 4 and helium 3, is able to reach temperatures of 3 mK by using the heat of mixing of the two isotopes. Whenever heat from the system is absorbed by the cryogenic liquid, the system becomes cooler due to the heat loss. The cryostat used in this experiment employed just Helium 4 to obtain low temperatures. The cryostat was cooled down in steps: first using nitrogen, primarily because it is cheaper, and then with Helium 4. The nitrogen is removed after the first stage and replaced with helium. The addition of helium with its lower boiling point enables one to readily reach a temperature of 4.2 K. To reach temperatures below 4.2 K, one must reduce the pressure of the system. The boiling point of helium is reduced with the reduction of the pressure.

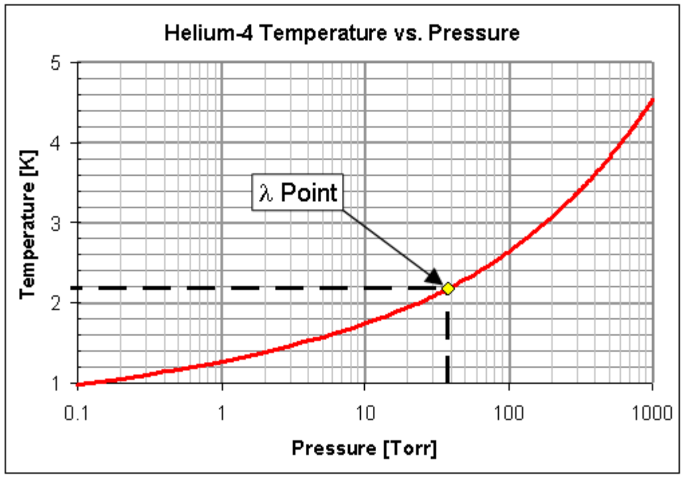

Figure 5: Vapor Pressure vs. Temperature of Helium 4 [18]

Therefore, as the system is pumped on to reduce the pressure, the temperature will decrease as described in figure 5. The cryostat is able to get down to temperatures around 1K. As mentioned before, dilution refrigerators can reach even lower temperatures. However for the purpose of these experiments, a simple helium 4 cryostat was sufficient.

3.4 Experiment

The experimental cell encloses the fiber and microbalance as shown in figure 4. One meter of the fiber of diameter 1.7 μm was used (aspect ratio: 6×10^5) and was wrapped around a spool as shown in figure 3. The fiber of 150 nm was weaker and therefore only 4 cm of it was used (aspect ratio: 2.7×10^5). The fiber rests on a chamber containing the QCM. There are two carbon resistors in the chamber acting as a thermometer and heater and another carbon resistor thermometer outside the QCM chamber. The helium input line allows helium to flow through the fiber into the QCM chamber and the output line allows helium to escape to the mass spectrometer, which detects the flow.

The experiment is done by pressurizing the input side with helium and then cooling the system down to 4 K and below. The first method monitors the flow rate on the output side detected by the mass spectrometer. The second method of measurement requires that the frequency of oscillation of the QCM be monitored. Anomalies around the lambda point, at the onset of superfluidity, were studied.

The first method of measurement was used for the 1.7 μm fiber; however this method was not sensitive enough when using the 150 nm fiber. The second method was used to measure the flow rate for the 150 nm diameter.

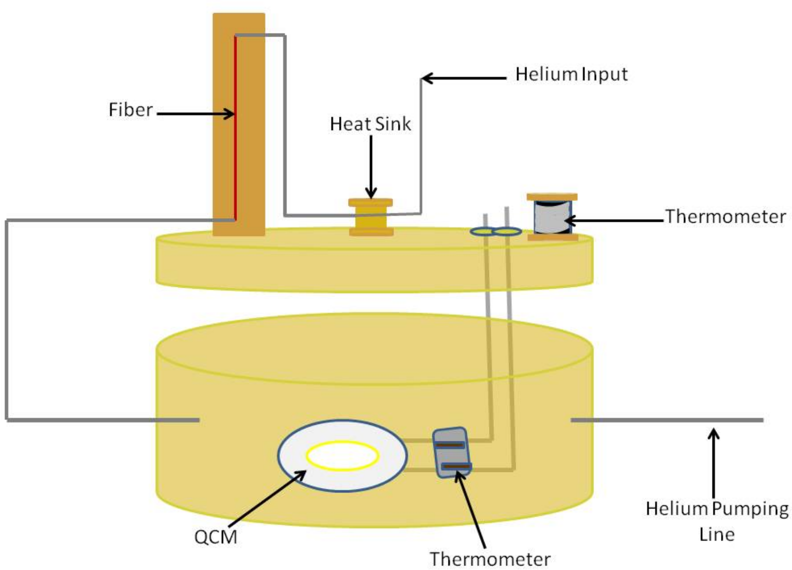

Figure 6: Experimental Setup

The main objective of the experiment was to allow helium to flow through the fiber as the temperature was cooled from around 3K to below the lambda point and then measure the flow rate. As discussed earlier there should be a rapid increase in the flow rate on cooling below the onset of superfluidity. The experiment is typically done by applying a certain pressure of helium to the inlet and monitoring the flow rate on cooling. The calibration of thermometers and saturation of the QCM were done beforehand.

Chapter 4

Results

We measured the flow of helium in fibers of two different lengths and diameters. The flow rate was measured as a function of temperature as shown in figures 8 and 9. The raw data measured by using the QCM was a frequency which can be translated to an effective mass by using calibrations [19]. This mass is in turn converted to a volume using the density of helium (figure 7) at a given temperature. Through knowledge of the dimensions of the fiber, one can readily calculate the flow rate of helium through the fiber.

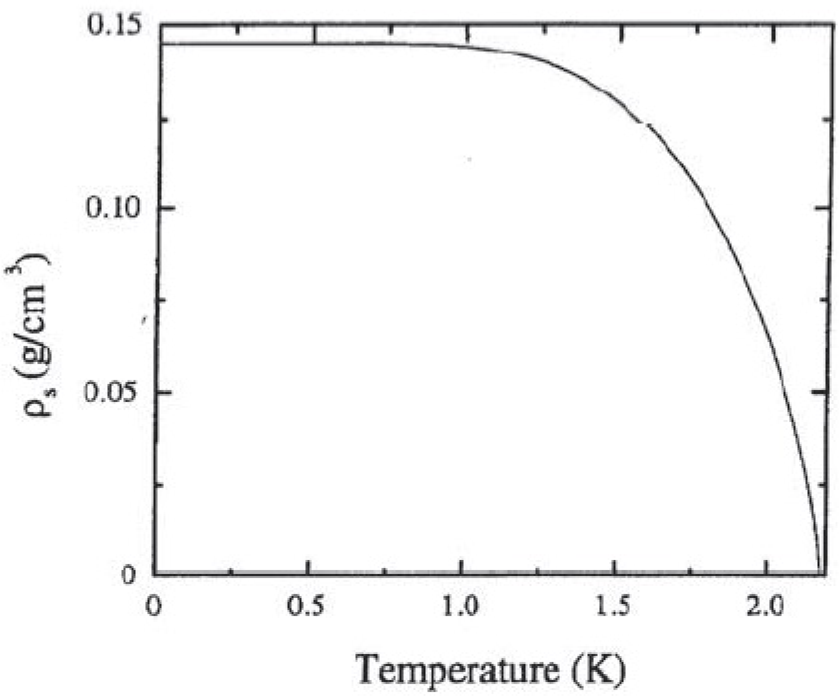

Figure 7: Superfluid density [20]

1.7 µm Fiber

There was a sudden increase in the flow rate at 2.28 K, see figure 7. This is higher than the 2.17 K, due to the fact that there may have been a temperature gradient within the system or likely the temperature was not accurately measured. The thermometers may not have been calibrated properly. The desired and expected result of measuring a sharp increase in the flow rate is observed. This fiber was primarily used as a simple test case for the setup and methodology because the aspect ratio is very high and one would expect superfluid flow characteristic of a conventional three dimensional system.

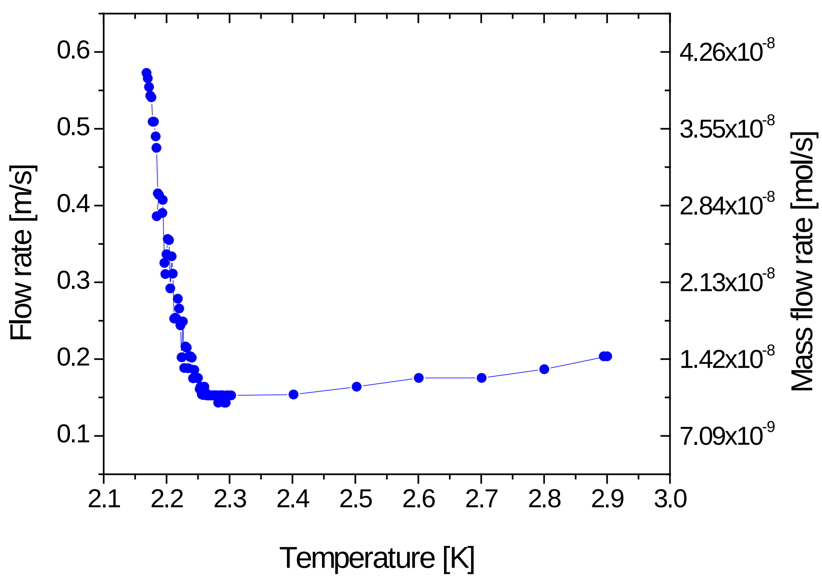

Figure 8: Liquid helium flow rate for fiber of 1.7 µm

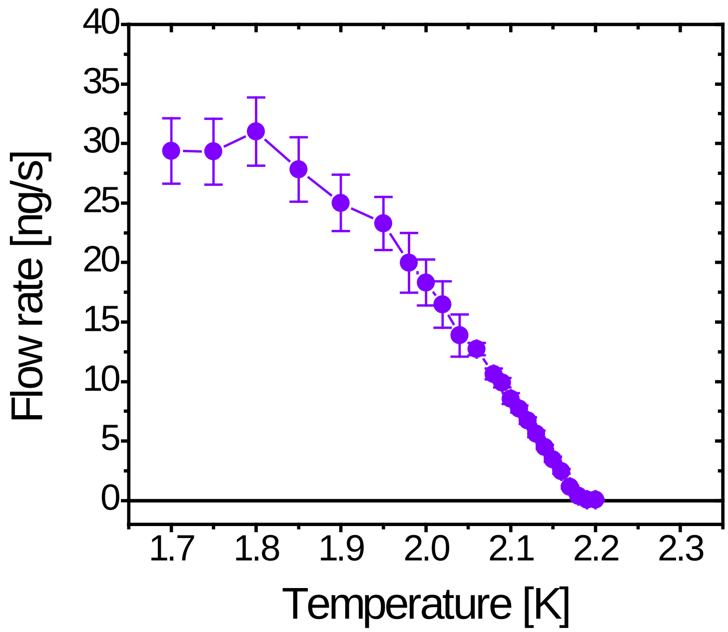

Figure 9: Mass flow rate of superfluid in 150 nm fiber

150 nm Fiber

The 150 nm fiber did exhibit superfluid flow with a transition temperature of 2.18 K as seen in figure 8. There was no measurable flow at temperatures greater than 2.2 K. This is because the normal fluid flow was suppressed in the long and narrow fiber. Also the dependence of flow rate was tested to ensure that the input pressure did not significantly affect the flow rate. The flow rate was measured at 1.7 K with different pressures applied. The flow rate with 11 mbar is slow, however above 0.6 bar the flow rate seems to be roughly constant. This suggests that the flow rate is determined by the superfluid critical velocity. The critical velocity was estimated to be of the order of 10-14 m/s and is comparable with the results of previous studies [21].

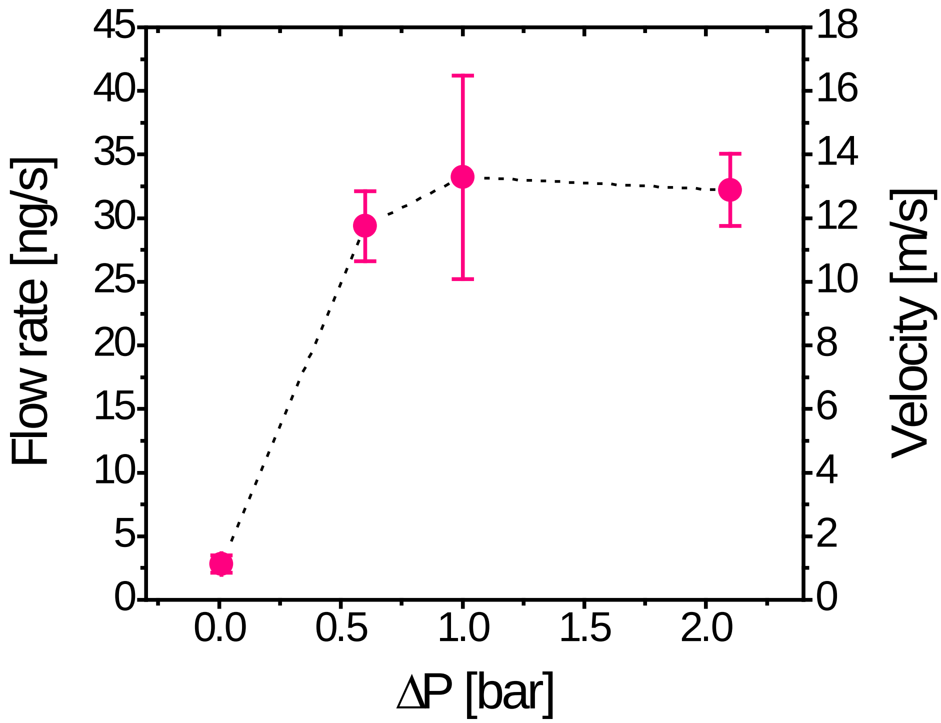

Figure 10: Flow rate pressure dependence

70 nm Fiber

The 70 nm fiber was made using the CVD technique described in the experimental section. The 70 nm fiber did not exhibit flow, possibly because the deposition layer was not uniform and the opening within the fiber had been pinched off. There was no significant flow detected down to the lowest temperature we studied (around 1 K). There could be at least two explanations for this negative result: the fiber was blocked off due to inhomogeneity in the diameter; the fiber was uniform in its diameter but the healing length of the superfluid exceeded the diameter and there was no onset of superfluidity.

Chapter 5

Conclusion and Further Studies

Superfluid flow was exhibited in our measurements of 150 nm and 1.7 μm. The superfluid transition in these fibers however was not very different from that of 3-D liquid helium. Fibers of smaller diameters should be tested to observe the crossover to the 1-D regime. New experiments with the fiber can be carried out to measure the Josephson effect with the fiber acting as a weak link.

The Josephson Effect mentioned earlier has resulted in numerous advances in the accurate measurement of fundamental constants, the development of exquisitely sensitive devices for measuring magnetic fields called superconducting quantum interference device (SQUID) magnetometers, digital electronics, superconducting tunnel junction detectors, and as Q-bits for building a quantum computer.

The work described here can be extended to study the nature of the link in a junction between two superfluids. In classical fluids (an ordinary resistor), a pressure difference (analogous to a voltage difference in the electrical problem) leads to fluid flow (current flow) from one side to another. In contrast, when one creates a Josephson junction between two superfluids, each characterized by its own macroscopic phase, there are fluid oscillations whose frequency is proportional to the pressure difference or the temperature difference between the two superfluids (see Figure 10). This effect has been observed first in Helium 3 and more recently in Helium 4 superfluids [8], [22].

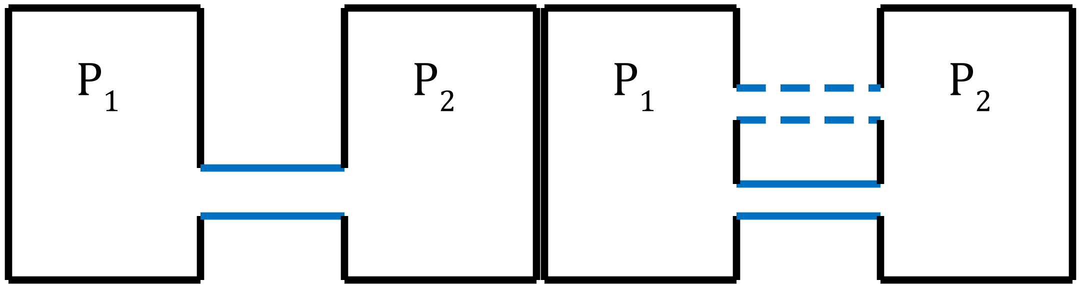

Figure 11: Weak Links:

Left Sketch of two fluid chambers, with a pressure gradient, connected by a weak link shown in solid lines. In a classical fluid, flow occurs from the higher-pressure region to the lower-pressure region. In contrast, oscillations are set up in the superfluid case with a frequency proportional to the pressure difference. Right: Adding a second link, shown as the dashed line results in an interferometer - changes in the oscillation amplitude provide a measure of the difference in the macroscopic quantum phases of the two superfluids. Adapted from Figure 2 in Ref. 3.

The Josephson link serves to weakly couple the two superfluids. Too strong a coupling would result in a single superfluid with one macroscopic phase. Too weak a coupling would result in two independent pockets of superfluid with no interaction. The most commonly studied weak links are comprised of thousands of holes each having a size of around 70 nanometers [8], [22]. Intriguingly, the sloshing back and forth of the superfluid occurs synchronously in each of the holes manifesting the emergent behavior of the weakly coupled condensates and also serving to amplify the observed signal. There are quantum oscillations with distinct origins and signatures at low temperatures (small healing length, strong link, with the physics governed by phase slip oscillations) and temperatures close to the critical temperature (large healing length, weak link, and Josephson oscillations).

Further questions of study include: How does the quantum coherence of a superfluid get affected when it is contained within a narrow tube? Could one observe oscillations with either a single tube or a collection of tubes acting as the link? How would the results depend on the diameter and the length of the tubes? How would the behavior of the interferometer be affected by asymmetric links? How does the behavior crossover from the strong link to the weak link regimes?

It would be interesting to study the complex interplay between the hydrodynamic and quantum pictures of a fluid in determining the dynamics of change in the superfluid phase and an understanding of the coherence of the oscillations between multiple links. The hypothesis that one could test is that the key determinant of the nature of the link is the interplay between the length scales of the link and the healing length of the superfluid. The healing length, which is proportional to the correlation length, can be tuned in a controlled manner by varying the temperature of the superfluid and diverges at the onset of superfluidity. If the signal is too weak for a single tube, one would have to revert to studies using carefully machined aperture arrays as the junction. Significant challenges in performing these experiments are the technical wizardry required to pull them off and the ever-present noise effects of rotation and vibration, whose shielding is difficult.

Surprising discoveries as well as major new insights often result from exploring matter under extreme conditions. Superfluid interferometry provides just such a setting of very low temperatures, precision nanoscale fabrication, carefully designed electronics, and the imaginative use of computers for running the experiments. The proposed studies have many applications in condensed matter physics and beyond [8] [22]. The superfluid helium analog of a SQUID, the SHeQUID, is very sensitive to tiny gradients in the phase of the superfluid within the torus. Such phase differences can arise from classical rotational dynamics or the quantum effects of vortex motion and forms the basis of an exquisitely sensitive quantum gyroscope. The SHeQUID can be used as rotation sensors for studying phenomena in general relativity.

A Luttinger liquid is a complex many body state which exhibits many novel properties including a breakdown of conventional Fermi liquid theory, the existence of spin-charge separation along with collective charge and spin fluctuations. A one dimensional system is special because of its tenuous connectivity and the huge importance of fluctuations lending itself to quite novel quantum behavior. The studies reported here could be thought of as a starting point for the study of such novel effects of quantum mechanics in one dimension. A study of superfluidity is a rewarding experience whether it is to test theories or to create new and exciting technologies.

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• Conducted experiment using dilution fridge
• Analyzed flow data

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• Analyzed magnetic susceptibility data

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Math Independent Study with Professor Adrian Ocneanu
Spring 2010
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- 2012 Penn State NSF REU: One Dimensional Behavior of Superfluid Helium
- 2013 Northeast Conference for Undergraduate Women in Physics at Cornell: One Dimensional Behavior of Superfluid Helium
- 2013 APS March Meeting: Duk Young Kim, Samhita Banavar, Moses H. W. Chan, One Dimensional Behavior in Superfluid Helium