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Author Wallace, Matthew

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UNIVERSITY OF CALIFORNIA, IRVINE

Impact and Spreading of Normal Fluid and Superfluid Helium Drops

THESIS

submitted in partial satisfaction of the requirements

for the degree of

MASTER OF SCIENCE

in Physics

by

Matthew L. Wallace

Thesis Committee: Professor Peter Taborek, Chair

Professor Zuzanna Siwy

Professor Gary Chanan

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Dedication

This work is dedicated to all who celebrate curiosity and spirit of science.

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Abstract of the Thesis

Impact and Spreading of Normal Fluid and Superfluid Helium Drops

by

Matthew L. Wallace Master of Science in Physics University of California, Irvine Professor Peter Taborek, Chair

Abstract: We present the results of our investigation of superfluid and normal fluid helium droplets impacting on a solid surface in an optical cryostat at temperatures between 1.2 K and 5.1 K at saturated vapor pressure. We use high-speed video to image the impacting drops over a large range of Reynolds and Weber numbers. We also use high-speed interferometry to measure the thickness and curvature of the droplets. We find that the initial impact stages for both normal and superfluid helium droplets are similar to the results for conventional fluids. We observe that at longer spread times, the normal helium droplets do not completely wet the surface and maintain a small but finite contact angle indefinitely. This result is surprising because helium is expected to fully wet nearly all surfaces. The spreading dynamics of normal fluid and superfluid droplets are temperature-dependent, and the lifetime of normal fluid long-term spreading follows a power law of spreading diameter vs. time with an exponent very close to 1/7, while the superfluid drops dissipate before long-term spreading can occur. Unexpectedly, we observe the Leidenfrost effect for normal fluid helium at high temperatures near the critical point.

Chapter 1

Introduction

The impact of fluid drops onto flat dry surfaces, thin liquid films, and deep liquid pools is a ubiquitous phenomenon in nature. Drop impacts also have numerous applications in industry and agriculture, including the spraying of crops with pesticides, fuel injection, inkjet printers, automotive painting, 3D printing, and many more. Drop impacts for conventional fluids have been studied extensively since the late 19th century. Specifically, the phenomena of spreading and splashing have been investigated for a number of fluids and under a number of different impact conditions. However, all of these experiments have been carried out at room temperature in an atmosphere of ordinary air. The impacts of superfluid drops, and of normal fluid liquid helium drops, has not been investigated. For drop impacts on flat dry surfaces and thin liquid films, previous research with conventional fluids has established the relationship of $r \propto t^{1/2}$ for the initial stages of impact, where the radius of the spreading drop is proportional to the square root of the time. Experimental data shows that this is true for fluid drop impacts with a wide rage of Weber and Reynolds numbers. In subsequent phases of spreading, the properties of the fluid, including surface tension and viscosity, can cause the drop to deviate from the $r \propto t^{1/2}$ relationship [1]. The intention of this experiment is to confirm this for superfluids, or to see if a fluid with nearly no viscosity will deviate from this relationship upon impact.

1.1 Drop Impacts in Conventional Fluids

For conventional fluids impacting on surfaces at room temperature there are three scenarios: the drop may impact a flat dry surface, a thin liquid film on top of a surface, or into a deep liquid pool. Upon impacting the surface, the drop may do one of the following: it may deposit on the surface without splashing, it may splash, or it may partially or completely rebound from the surface. These outcomes are determined by a number of quantities of both the fluid and the surface. The relevant quantities for this are the Weber number, Reynolds number, surface roughness (for a flat dry surface), and receding dynamic contact angle. The Weber number We and the Reynolds number Re are

$$We = \frac{\rho U^2 L}{\sigma} \tag{1.1}$$

$$Re = \frac{\rho UL}{\mu} \tag{1.2}$$

where ρ is the density of the fluid, L is the characteristic length, U is the velocity, σ is the surface tension, and μ is the kinematic viscosity. The Weber number is the ratio of the fluid's kinetic energy to its surface energy, and the Reynolds number is the ratio of the fluid's inertia to its viscosity.

We now consider the mechanics of the impacting drop. Figure 1 shows the possible scenarios for drop impact on a flat dry surface. The drop moves at speed u and is incident on the surface. Just after the drop contacts the surface, the drop closely resembles a truncated sphere. Then a thin liquid sheet called a lamella is ejected from the drop. From here, the drop can go into one of two regimes. It can splash, as shown in the flow path on the right, which we shall call "splashing." It can also deposit and spread without splashing, which we shall call "deposition." If the drop splashes, the remaining droplets remain scattered around the drop impact area. If the drop deposits on the surface, it can take one of three further paths: it can spread, it can partially rebound, or it can fully rebound. The path taken by the drop depends primarily on the Weber number and the Reynolds number. Drops with



Figure 1.Drop impact scenarios [9]. Upon impact, a drop may deposit (left) or splash (right). A drop that deposits may also rebound.

a higher Weber number and lower Reynolds number tend to deposit on the surface. Drops with a low Weber number and high Reynolds number are more likely to rebound [7]. The preceding treatment has considered drops incident on a flat dry surface; however, the drops may also impact on a thin liquid film, which is the case for our experiment. However, an analysis of drops impacting a flat dry surface is useful for present purposes.

In considering the scenario of impact on a flat dry surface, Rioboo et al. found that there were four distinct phases of spreading: kinematic, spreading, relaxation, and wetting/equilibrium [1]. The first phase, the kinematic phase, is characterized by the relationship $\frac{d}{D} \propto (t^*)^a$ with $t^* = \frac{tV}{D}$ being the nondimensional time, with drop velocity V and initial drop diameter D. The generally accepted value of a is $\frac{1}{2}$, though various authors give experimental values between 0.43 and 0.5 [6]. This relationship arises from the geometry of the impact and holds true for fluids with a wide range of Weber numbers and Reynolds numbers. The kinematic phase lasts approximately until d > D at which point the spreading phase begins. During the spreading phase, the spreading of the drop is influenced by the properties of the fluid, including the Weber number, Reynolds number, and dynamic receding contact angle θ_{rec} . During the relaxation phase, the drop may begin to come to rest on the surface, or if the drop will fully or partially rebound, the diameter of the drop will decrease during this phase. During the wetting phase, the drop wets the surface and becomes static. The relationship $\frac{d}{D} \propto (t^*)^{\frac{1}{2}}$ holds true during the kinematic phase for nearly all fluids regardless of viscosity or surface tension. The lamella is ejected at characteristic time $\frac{\mu}{U^2}$ [4].

1.2 Tanner's Law

The long-term spreading of a droplet, which coincides with the "wetting" phase in Figure 3, is described by Tanner's Law, which is a power law stating that the radius of the spreading drop as a function of time is proportional to t^n , with n = 0.1 - 0.15. The typical value of n given in the literature is 1/10, which is largely in agreement with experimental values found using very viscous fluids and longer spreading times. Other theoretical values of n can be derived depending on the parameters used. Cazbat and Stuart [13] show that an exponent of 1/10 can be obtained by balancing the viscous force against the capillary force to obtain

$$R = \Omega^{\frac{3}{10}} \left(\gamma \frac{t}{\eta} \right)^{1/10} \tag{1.3}$$

with spreading radius R, volume Ω , surface tension γ , time t, and viscosity η , and this is the usual form of Tanner's Law. But if the viscous force is balanced against gravity, we obtain

$$R = \Omega^{\frac{3}{8}} \left(\frac{\rho g t}{\eta}\right)^{1/8} \tag{1.4}$$

with density ρ and gravitational acceleration g. As will be show later, this exponent of $\frac{1}{8}$ is in better agreement with our experimental results. The exponent that is in best agreement with our experimental results is $\frac{1}{7}$, which was arrived at by considering gravity to be the dominant force [14].



Figure 2. Helium Phase Diagram.

1.3 Drop Impacts in Superfluids

Superfluidity is an exotic state of matter in which a fluid has zero viscosity; this allows the fluid to flow without friction and without frictional heating. Liquid helium transitions to superfluid cooled below the lambda temperature, which is $T_{\lambda} = 2.17K$ at saturated vapor pressure. We employ the two-fluid model for superfluids, which models a superfluid as a combination of normal fluid and superfluid. Figure 5 shows a phase diagram of liquid helium around the λ -transition, and Figure 6 shows a plot of the relative fractional density of superfluid helium $\frac{\rho_s}{\rho}$ and normal helium $\frac{\rho_n}{\rho}$.

1.4 Motivation for Experiment

As Tanner's law involves the spreading of drops by viscous dissipation, the motivation for this experiment was largely to examine the spreading of drops which had no viscosity, as in superfluids. According to Tanner's law, a drop with no viscosity should spread infinitely fast. We decided to test this by dropping superfluid helium onto a substrate and examining the spreading.



Figure 3. Superfluid density as a function of temperature. Just below the λ -transition, nearly all the fluid is normal fluid; but at temperatures below 1 K, nearly all the fluid is superfluid.

Chapter 2

Experimental Setup

2.1 Cryostat, Pump, and Other Equipment

The constraints of the experiment present a number of engineering challenges. Cryostats are typically employed for experiments in the temperature range of 1-4 K, which is the temperature range for this experiment. The cryostat must have windows which give optical access, both from the side and from the bottom, so that high-speed video of the impacting drops can be taken. A pump to deliver drops on demand needed to be constructed, with the constraint that the pump cannot dissipate any heat and should have few or no moving parts. A schematic representation of the cryostat is given in Figure 4, and a photograph is shown in Figure 5.

The experimental setup is shown in Figure 6, and was as follows: The helium was supplied from a tank outside the cryostat, and the pipe containing the helium ran into the cryostat, through a heat exchanger to cool the helium and liquefy it, and to the pump. The drops were delivered from a dropper nozzle inside the cell, and the drops were allowed to fall onto sapphire (or the QCM surface). An LED was used to supply the light for the experiment. The camera, a Vision Research Phantom v2511 was mounted to take video from the side or from the bottom as shown in Figure 6. An LA Vision QM1 long-distance microscope was mounted on the camera.



Figure 4. Schematic of the cryostat, which resembles a set of nested dolls.



Figure 5. Picture of the cryostat. The cell, which contains Mirror 1 (listed in Figure 6), the LED light, and the substrate, can be seen in the center of the image.



Figure 6. Experimental Setup. The impacting drops inside the cryostat's cell were imaged from two angles with a long-distance microscope and a high-speed camera.

The camera used for imaging from the side was mounted at a downward angle of about 6.4 degrees so that the interference lines could be seen. The impedances used were glass nanotubes with an inner diameter of 5 to 10 μ m and were manufactured by Polymicro Technologies. The impedance allowed the dropper input line to be pressurized and to stay at a stable pressure while regulating the flow of helium. If the proper pressure was applied to the dropper input line, the drops would fall from the dropper at predictable intervals. Typical drop intervals were about 30 seconds for superfluid drops and 30 minutes for normal fluid drops. Two lenses were used to to partially collimate the incoming light from the LED. The mirror inside the cell (Mirror 1) was made from an aluminum hard drive, and a hole was drilled through the center of the mirror so that the impedance could protrude through the hole. A second pump line with a Swagelok 0.5 micron filter was used to add or remove helium from the cell independent of the dropper line. To obtain drops from the dropper line, helium was put in the line to a pressure of 2-50 Torr above saturated vapor pressure, depending on the desired drop frequency.



Figure 7. The gold circle is the QCM, which uses vibrating quartz to detect very small amounts of mass. Also shown are the aluminum stand and copper window blank.

Leveling feet were installed on the cryostat to ensure that the impact substrate was perpendicular to gravity. The cryostat was leveled when it was fully cold and when liquid helium drops were visible on the impact substrate. The leveling procedure was to watch the behavior of the drops on the surface, then level the cryostat, then repeat until the drops did not appear to move one way or the other on the surface.

2.2 Quartz Crystal Microbalance

An instrument was needed to measure the fluid layer that would invariably form on the substrate when the helium in the cell was a saturated vapor pressure. A quartz crystal microbalance (QCM) was employed for this task. The QCM can detect extremely small masses on its surface by vibrating the crystal at a certain frequency and observing the changes in frequency as mass is deposited on the surface. The thickness of the fluid layer on the crystal surface is proportional to the change in vibrational frequency Δf of the crystal. The QCM is sensitive enough to detect a single atomic layer on its surface. The film thickness h as a function of frequency shift Δf is given by



Figure 8. Data from the QCM for 1.600 K, showing the thickness of the helium film on the QCM surface as a function of temperature. The K-T transition occurs here at about 4.6 Torr.

$$h = \frac{\Delta f}{\rho \, C_f} \tag{2.1}$$

for fluid density ρ and constant C_f , which for this QCM was $\frac{5.66 \times 10^{11} \text{ Hz m}^2}{\text{kg}}$.

Figure 8 shows the sensitivity of the QCM. At a constant temperature of 1.600 K, helium gas was added to the cell, starting from vacuum, causing a fluid layer to build on the QCM as more gas was added. Van der Waals forces keep the helium layer essentially solid at very low pressures. The film layer gets thicker as the vapor pressure gets higher, until the upper part of the film decouples from the lower part in the Kosterlitz–Thouless transition, shown at 4.6 Torr in Figure 8.

2.3 High-Speed Video

A high-speed Phantom v2511 video camera was used to image the drops. This camera is capable of taking video at 1,000,000 frames per second. Typical frame rates for this experiment were 25,000 FPS, 1,000 FPS, and 100 FPS. For the kinematic (short-term) spreading, a rate of 25,000 frames per second was used. The length of video is limited by the memory of the camera; at 25,000 FPS, only 1.3 seconds could be recorded and stored. This is sufficient because the time from drop impact to the completion of the kinematic spreading is less than 20 ms. A long-distance microscope was mounted on the camera at a working distance of about 1 meter.

2.4 Bellows Pump

A previous version of drop delivery (before the nanopipe) was a low-temperature bellows pump, which had the advantage of being able to deliver drops nearly on demand. This pump was constructed as follows: a YBCO superconductor was mounted to a bellows assembly, which was mounted on rails to guide the bellows as the bellows were compressed. A coil of superconducting wire with about 2,000 turns was mounted behind the YBCO. When a current is passed through the superconducting wire, a magnetic field is created; and since the wire is superconducting, it does not dissipate any heat. The Meissner effect of the superconducting YBCO creates a magnetic field in direct opposition to the field created by the coil of wire, resulting in a net repulsive force between the coil of wire and the YBCO. This repulsive force compressed the bellows, which caused helium in the bellows to flow up the pipe and out the dropper nozzle. The pump is shown in Figure 9.

The pump was abandoned in favor of the glass impedance tubes for a few reasons. The drop size and ejection velocity was difficult to control with the pump, and multiple drops often were ejected from the pump nozzle. The superconducting wires often suffered loss of superconductivity when ohmic heating in the non-superconducting region of the wires caused the superconducting portion to become too hot. The tubes provided a more reliable way to consistently produce uniformly-sized single drops.



Figure 9. Bellows Pump.

Chapter 3

Experimental Results and Discussion

3.1 kinematic spreading

Figure 10 shows a typical impacting drop during the kinematic phase. During this kinematic phase, the drop spreads out under its own inertial forces, then comes to a partial rest. This phase of the spreading lasts less than 20 ms. The result of one set of drop impacts is shown in Figure 11.

Consider Figure 11. As is apparent from the plot, the spreading of the superfluid drops is similar to the spreading of the normal fluid drops, which is similar to the spreading for conventional fluids. The superfluid droplets spread slightly faster, and have a larger maximum spreading radius, than the normal fluid drops because overall viscosity is lower.



Figure 10. Drop at 2.002 K, 0.8 ms after impact.



Figure 11. Plot of the kinematic spreading of helium. Each set of colored data points represents one drop. The drops ranged in temperature from 1.38K (red) to 2.46K (blue/violet). Time is measured logarithmically on the horizontal axis, and spreading diameter logarithmically on the vertical axis. The slope of the blue line is 1/2.

However, the drop's radius does not spread infinitely fast. If we refer again to the power law for spreading with $a = \frac{1}{2}$, we see that both normal fluid and superfluid obey this law.

3.2 Drop Shape and Thickness

Consider the following normal fluid drop on a sapphire surface:

The first surprise for this drop shape is the existence of a clear and persistent contact line. Liquid helium is believed to wet everything except for elemental cesium [12], and the existence of a persistent contact line is in significant disagreement with other experiments. The shape of the upper surface of the droplet can be measured using interferometry. Using the equation for Bragg diffraction,

$$2d\sin\theta = n\lambda\tag{3.1}$$

with fringe spacing d, camera angle θ and wavelength λ , the change in the surface height for each light or dark fringe is calculated to be 77.12 nm for the red LED that was used in this experiment. From this, we see that the top of the drop is extraordinarily flat. If we



Figure 12. Helium drop at 2.333K on sapphire surface. The lines are interference lines and show the curvature of the droplet, with each light or dark fringe representing a change in height of 77.12 nm.

examine the edge of the drop, we see that the interference lines do not converge near the edge. Rather, they end abruptly. This implies the existence of a "cliff" at the edge of the drop, and shows that the drop is shaped like a "pancake" with a flat top and a sharp cliff at the edge, as in Figure 13. We can use conservation of volume to calculate the thickness of the pancake.

Figure 13 shows the cap of the drop on the surface, or the curvature of the drop based on the interference lines. Using conservation of volume, this cap contains only about 10% of the total volume of the original drop, further implying the existence of a cliff at the drop's edge.

It has been shown theoretically that a superfluid drop can form such a pancake because of the superflow out of the drop [10].

We can measure the shape of the cliff using image subtraction and ray tracing. Consider the bottom view image of a superfluid drop at a temperature of 1.850K in Figure 14. This is a processed image, wherein a background image (before the drop spread) was subtracted from the image of the fully spread drop. The horizontal line represents a line of pixels for which the image data was taken and plotted. A zoomed-in plot of this image data is shown in Figure 15.

Figure 16 shows a model of the drop that is congruent with our experimental data, namely that the drop height is 10 um, the diameter is 4.44 millimeters, and the edges are 200 um



Figure 13. The cap of a drop on the surface, with each point representing an interference line, as shown in Figure 12. Note that the horizontal scale is five orders of magnitude larger than the vertical scale, indicating the extraordinary flatness of the drop's cap.



Figure 14. Bottom view of a drop at 1.850 K at the end of the kinematic spreading phase, 20 ms after impact. This image was created by subtracting the background image from the image of the impacting drop. The red line represents a line of pixels whose brightness is plotted in figure 15.



Figure 15. Plot of the image data from the drop in Figure 14. The two peaks in Figure 15 correspond to the "cliff" on each side of the drop, as shown in Figure 14. Ray tracing can be used to model this cliff, as shown in Figure 16. The horizontal scale is 80 pixels/mm.



Figure 16. Ray trace of a model of a drop (top), and the resulting intensity (bottom). The bright peaks represent a gentle slope near the edge of the drop, while at the actual contact line, the light is bent away, creating a brightness trough.



Figure 17. Intensity plot of spreading 2.075K, 1 ms after impact. For the horizontal axis, the scale is 80 pixels/mm.

wide. Using these parameters and modeling the drop edges as a hyperbolic tangent function, we obtain an intensity histogram that looks very similar to the data that we collected for expanding drops, as seen in Figure 17. The data matches the model in that the intensity peaks near the edges are about 10% higher than the background intensity.

Figure 17 shows an intensity plot (with the background subtracted) for a drop of 2.075K, similar to Figure 13. The light intensity between the peaks is about 1% higher than the background light, which is a result of the vacuum-helium-sapphire optical pathway being more transparent than the vacuum-sapphire optical pathway. As can be seen from the histogram, the actual edge of the drop appears dark because the light is refracted away. The edge is concave rather than convex because of the presence of the superfluid film and Van der Waals forces.

Interference lines were clearly observed when looking at the drop from the side, but were not observed when looking from the bottom. This is because much more light is reflected from the helium surface and sapphire surface when the light approaches the surface at a high angle of incidence than from normal incidence. In the side view, the light approached the helium at an angle 83.6 degrees, which is nearly glancing incidence. As the angle of incidence approaches 90 degrees the reflection coefficient approaches 1, so a significant portion of the light was reflected in the case of the side view. For the case of observing the drop from below, the light approached the helium from normal incidence, and the reflected light was nearly



Figure 18. Dissipation time as a function of temperature. The blue line shows the λ -transition at 2.17 K. Fast dissipation is clearly a superfluid phenomenon, with the presence of even a very small fraction of superfluid substantially reducing the lifetime of a drop.

four orders of magnitude smaller than the light observed in the side view, so no interference lines were observed.

3.3 Drop Lifetime on Substrate

One of the biggest surprises of this experiment was that the lifetime and spreading of both the normal and superfluid drops was finite, and all drops eventually shrank and disappeared. There was, however, a stark difference in lifetime between the superfluid drops and the normal fluid drops.

Figure 18 shows the enormous difference in dissipation time between normal fluid and superfluid drops. The normal fluid drops live for about 15 minutes on the surface, while the superfluid drops last only a few seconds. As is seen in the plot, the coldest supefluid drops, which have the greatest fraction of supefluid, last less than a second. The superfluid drops last longer as they get warmer and have a greater fraction of superfluid, with superfluid drops near the lambda transition lasting for about 12 seconds. Then after the threshold is crossed into normal fluid, the drops suddenly last for about 15 minutes. The much shorter



Figure 19. This figure combines short-term and long-term data for two identical drops at 2.500 K to form a plot for the lifetime of a drop. Note the different phases of spreading.

lifetime of the supefluid drops is due to superfluid flow out of the drop through the thin film on the surface.

Figure 19 shows the lifetime of a single drop of helium at 2.500 K, and Figure 20 shows a close-up of the long-time spreading of the same drop. As can be seen, the drop spreads kinematically up to a time of about 10 ms. After that, the drop appears to sit nearly still for a time, then spreads in accordance to Tanner's law, except that the spreading exponent is 0.15 rather than 0.1. Maximum drop expansion speeds for our experiment were 0.24 m/s, less than the critical velocity for superfluid helium [10]:

$$v_c = \frac{C}{h} \tag{3.2}$$

with critical velocity v_c , drop thickness h, and constant $C = \frac{10^{-8}m^2}{s^2}$ for He. For our drop impacts, this value is about 0.6 m/s. The spreading exponents can also be seen on Figure 17. During the kinematic phase, drop spreading goes as $r \propto t^{1/2}$, as expected, and the orange line has a slope of 1/2. For the long-term spreading, the red, green, and blue lines represent exponents of 1/7, 1/8, and 1/10. As can be seen on the plot, 1/7 seems to be the exponent with the best fit, which is in agreement with our quantitative analysis, which is that the exponent is $0.146 \pm .0028$ with a 95% confidence interval.



Figure 20. Long-time spreading of a drop at 2.500K. An exponent of 1/7 is the best fit.

Recall Eqns. 3 and 4 for long-time drop spreading. The data shows that the better fit for the exponent is Eq. 3 with an exponent of 1/8; however, the closest fit to the actual experimental value of 0.146 would be 1/7. If we take Eq. 4 as the model for the spreading and substitute in the volume, density, and viscosity of helium, and the acceleration due to gravity, we get

$$R = 0.342t^{0.125} \tag{3.3}$$

The actual experimental value for this equation is

$$R = 0.378t^{0.146} \tag{3.4}$$

This is reasonably good agreement. The biggest discrepancy is in the exponent, where the experimental exponent is closer to 1/7 than 1/8. However, a theoretical value for the coefficient for the regime of a 1/7 exponent has not been established.



Figure 21.Representations of droplets impacting on a surface with a liquid film. The drop on the left is impacting on a very thin film, as thin as two atomic layers. The drop on the right is impacting on a thick film, as thick as 50 nm

3.4 Surface Film Thickness and Long-Time Spreading

The thickness of the pre-existing liquid film on the substrate substantially affects the longtime spreading of the drop.

The thickness of the film can be controlled by heating the substrate, and the film thickness can be measured by the QCM. The following figure shows the spreading diameter as a function of time with various amounts of heat being put into the substrate.

With no power (heat) being put into the substrate, the liquid film on the substrate is 50 nm thick. Drops that impact on this film spread by a power law with an exponent of 0.15, or about 1/7. This is in agreement with the theoretical predictions of Ehrhard and Davis if gravity is the dominant force [14].

3.5 Superfluid Exodroplets

A curious phenomenon is observed when superfluid droplets impact on a substrate. Small droplets form outside the contact line of the expanding drop, and the droplets are larger and more pronounced as the temperature gets lower and the superfluid fraction gets higher. The following figure shows these superfluid droplets:

These superfluid exodroplets appear at some distance from the contact line as the drop expands, and they grow in size, rather than translate, as the main drop expands. Then,



Figure 22.Drop spreading diameter as a function of time at various substrate heat inputs. Putting a small amount of heat into the substrate reduced the pre-impact film, causing the drop to dissipate much faster.



Figure 23. A superfluid drop impact seen from below, with the average background subtracted out. The red arrows point to superfluid exodroplets, which can be seen all around the contact line.



Figure 24. Liquid helium drop displaying the Leidenfrost effect.

when the main drop starts to shrink, the exodroplets appear to be sucked back into the main drop as it shrinks.

3.6 Exotic Behavior: Leidenfrost Effect

The Leidenfrost effect occurs when a droplet of fluid encounters a surface much hotter than the fluid's boiling point, causing a cushion of vapor to keep the drop insulated from the hot surface and making the droplet of fluid levitate. This effect has not been previously observed for liquid helium in the published literature, but we observed it as part of our experiment.

Figure 24 a helium drop levitating above a sapphire surface on a cushion of helium vapor. The Leidenfrost effect was observed for drops at temperatures between 4.5-5.2 K. This was remarkable because, in contrast to water's Leidenfrost temperature T_L of 425 K [16], Leidenfrost helium drops were observed even when the the substrate temperature was observably the same as the drop temperature.



Figure 25. Bouncing helium drop at 4.492 K. The drop impacts (left) then rebounds (center and right). Each frame is 10 ms apart.

3.7 Exotic Behavior: Bouncing

As stated earlier in this paper, bouncing occurs in drop impact situations where the Weber number is small and the Reynolds number is large. Liquid helium droplets were observed to bounce from the sapphire substrate when the temperature was above the 4.2 K and the pressure in the cell was sufficiently high. Weilert et al. showed that gas outflow from liquid helium drops can cause non-coalescence [15].

Chapter 4

Conclusion

We have investigated the impact and spreading of normal and superfluid helium drops in a temperature range between 1.2 K an 5.1 K using high-speed video. We found that the short-term spreading behavior for normal fluid helium, superfluid helium, and conventional fluids were all about the same. We saw that there was significant difference in long-term spreading behavior between superfluid drops and normal fluid drops because the superfluid outflow caused the superfluid drops to dissipate much faster than the normal fluid drops. The normal fluid drops did spread in a Tanner-esque way, but with a power law that had an exponent of 0.15 rather than the expected 0.10. We observe that neither the normal helium nor the superfluid helium fully wet the surface, but instead maintain a finite contact angle indefinitely. We also observe exotic behavior of the droplets, including the emergence of exodroplets in superfluid, the Leidenfrost effect, and the bouncing of helium droplets.

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