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Direct Optical Imaging of Superfluid ^{4}He Droplets on a Cesium Surface

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The recent discovery that ^{4}He does not wet the surface of cesium makes possible the study of superfluid droplets. We have used a long focal length microscope to study superfluid ^{4}He droplets on a cesium surface. We find that ^{4}He droplets do not flow freely over the surfaces we prepare. Rather, they remain stationary even when the surface is inclined by as much as 10° to the horizontal. The contact angle, the angle between the surface and the liquid-vapor interface is also highly hysteretic. At 1.2 K, where the advancing angle is near 25°, the receding angle varies between 0° and 7°, depending on the cesium film.

1. INTRODUCTION

The recent discovery [1,2] that liquid ^{4}He does not wet the surface of cesium metal makes possible a new class of superfluid flow experiments. Adsorption isotherm experiments[3] and transport measurements[4] show that even in the presence of bulk, saturated liquid a cesium surface is covered by only a dilute concentration of nonsuperfluid ^{4}He atoms. For the first time, it is possible to study the flow of bulk superfluid on a bare wall. We have been studying superfluid ^{4}He droplets on the surface of evaporated cesium films. Our technique is to photograph droplets on the surface while forcing them to flow either by adding or removing liquid from the droplet or inclining the surface. The striking feature of our results is the strong resistance to flow exhibited by the droplets. Indeed if the only experiments available on the flow of ^{4}He were droplet experiments, superfluidity would not have been discovered. The resistance is associated with the triple line, the perimeter

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of the droplet on the surface. Our purpose here is to show some new results and compare them with experiments with H_2 on the same surfaces.

2. EXPERIMENT

The apparatus and cesium film preparation techniques have been described elsewhere.[5] Briefly, we have built an optical cryostat to study superfluid droplets on a cesium surface. The cryostat contains a continuously filling ^{4}He evaporative refrigerator that can cool a closed sample cell to just below 1.2 K. We can make and maintain clean cesium surfaces in the cell. Microscopic inspection shows that the surfaces are free of all but a few isolated defects larger than a few microns. Droplets are formed on the surface of the cesium by injecting ^{4}He liquid through a capillary. Windows allow the droplet to be viewed from two angles, nearly tangent to the cesium surface and at an angle of 30° above tangent. Images of the droplet are recorded through either window with a long focal length microscope and digital camera or VCR camera.

3. RESULTS AND DISCUSSION

Contact angle hysteresis results when the triple line motion across the surface is resistive. The contact angle is the angle between the free surface and the substrate measured through the liquid. On all real surfaces the contact angle is hysteretic. It is larger when the liquid advances across the surface than when it recedes.[6]Contact angle hysteresis is usually attributed to variations in the wettability of the surface due to impurities or to roughness. The contact angle of ^{4}He on our cesium surfaces is highly hysteretic. Figure 1 shows two images of a ^{4}He droplet on a cesium surface. The free surface of the droplet and its reflection off the cesium are both seen, accounting for the droplet's symmetrical appearance. A line drawn between the sharp points where the free surface and its reflection meet lies in the plane of the surface. The angle between it and the free surface at either end is the contact angle. The dark object emerging from the top of the droplet is the capillary. In the top image liquid is being added to the droplet through the capillary and the diameter of the droplet is expanding at a rate of 1mm/minute. The contact angle is the advancing contact angle. The bottom image shows the receding contact angle as liquid is removed from the droplet at about the same rate. At these low rates, the contact angles are independent of the rate. The contact angle hysteresis is evident. We have made measurements like these on a number of cesium surfaces.

As reported previously[5,7] on the majority of our surfaces the receding

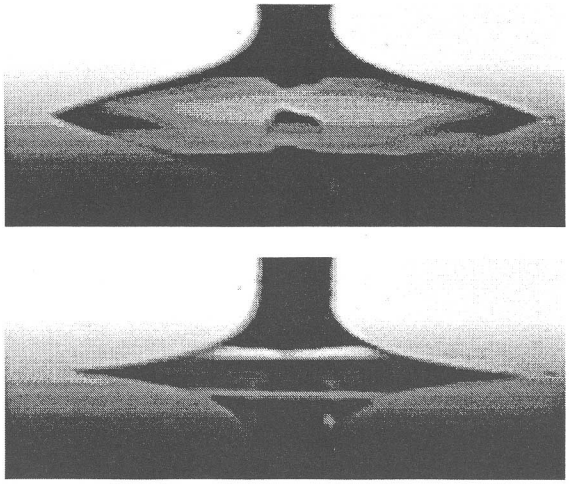

Fig. 1. Advancing, top, and receding, bottom, contact angles of a ^{4}He droplet on a cesium surface. Contact angle hysteresis indicating resistive motion of the triple line is evident.

contact angle has been 0°. In these cases we can form a droplet and make it expand across the surface by adding liquid through the capillary. When the bulk liquid is removed a remnant film is left behind over the area covered by the droplet at its maximum size. This is evident when liquid is admitted through the capillary a second time. Instead of advancing across the part of the surface covered by the previous droplet with a fixed contact angle, the liquid immediately spreads until it reaches the boundary of the previous droplet. Then as more liquid is added, the contact area with the cesium remains fixed but the curvature of the free surface and the contact angle increase. Only when the contact angle has reached the advancing angle does the contact area with the cesium begin to increase again. More recently we have made cesium surfaces with nonzero receding angles. Figure 2 shows the temperature dependence of the advancing and receding contact angles on two different surfaces with nearly identical wetting temperatures. The advancing contact angles are nearly identical on both surfaces. They are also nearly identical to those measured elsewhere on evaporated films[8] but considerably smaller than contact angles reported in another experiment.[9] On one of the surfaces in the figure, the receding contact angle reaches 7° at low temperature and on the other it is zero across the entire temperature range. Both cesium films were approximately 40 monolayers thick, both were evaporated on a $\sim$ 4 K substrate and subsequently annealed near 80 K for 40 minutes. Evidently some relatively subtle, uncontrolled structural change

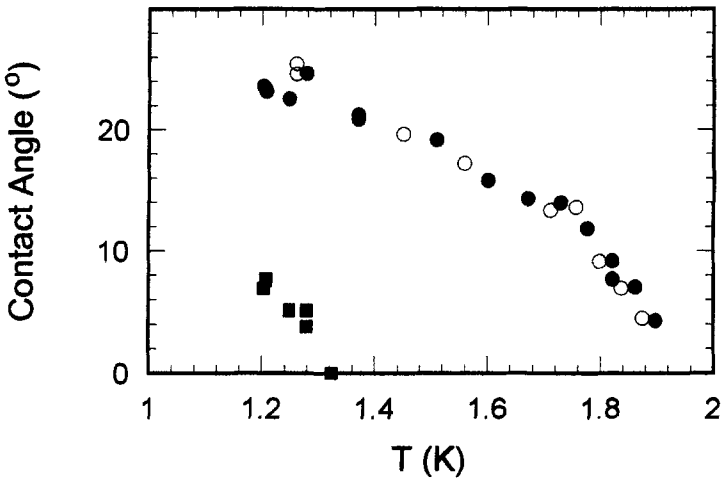

Fig. 2. The temperature dependence of the advancing and receding contact angles on two different cesium surfaces. On one surface, solid symbols, the receding contact angle, squares, is nonzero at the lowest temperatures. On the other surface, open circles, the receding contact angle is zero at all temperatures.

is responsible for the different behaviors of the receding contact angles.

There is a notable difference between the behavior of droplets with zero and nonzero receding angles. Over the temperature range where the receding contact angle is nonzero a remnant ^{4}He film is not left on the cesium after a droplet recedes. In contrast to the zero receding angle case, when the receding angle is nonzero and a second droplet is advanced, the contact angle is identical to the contact angle measured during the spreading of the first droplet.

Figure 3 shows a second type of flow experiment. Here the cesium surface has been inclined at about 10° to the horizontal and a droplet has fallen from the capillary and landed on the surface. In the top image the droplet has a 0° receding angle and in the bottom image a 7° receding angle. In both cases the droplet sticks to the substrate. The first drop to fall slips a short distance across the surface and comes to rest. As each succeeding drop hits and joins the droplet on the surface, the enlarged droplet again slips a short distance and then comes to rest. Only after several drops have been added does the droplet slide off the substrate. When the receding angle is 0°, droplets formed after the first droplet has slid off the substrate immediately slide off down the same path. When the receding angle is finite, they do not. Evidently the remnant film left behind by the 0° receding angle is responsible

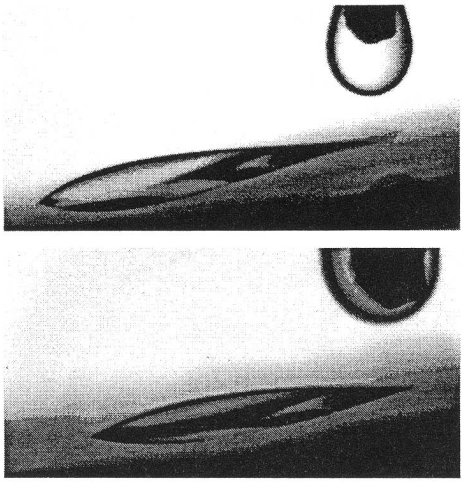

Fig. 3. Motionless droplets on inclined cesium surfaces. In the top image, the receding contact angle seen at the top of the droplet is zero. In the bottom image the receding angle is nonzero. Nevertheless, the droplet does not flow.

for the change in the surface. In both cases, the droplets stick so well to the surface that even vigorous shaking of the substrate fails to dislodge them.

Finally, we have measured advancing and receding contact angles for H_2 on a cesium surface that had a receding angle of 3° for ^{4}He at 1.2K. The results are shown in Fig. 4. It is clear that the hysteresis is much smaller for H_2 than it is for ^{4}He, but it is not clear why the contact angle hysteresis is so different. It may be that the difference is due to the larger energy and temperature scale for the H_2 case or it may indicate that a superfluid triple line is more profoundly affected by surface imperfection than is a normal one, perhaps due to vorticity. Exploration of this highly speculative but intriguing possibility must await the preparation of surfaces with wetting temperatures well above T_λ.

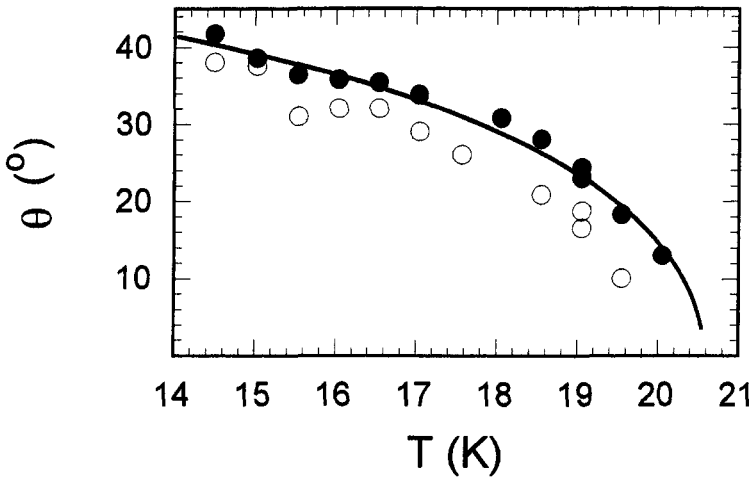

Fig. 4. Advancing and receding contact angles for H_2 on Cs. The advancing angles are closed symbols and the receding angles are open symbols. The uncertainty in the angle is the size of the symbol. In contrast to the ^{4}He data, the hysteresis is quite small.

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