GAPLESS SURFACE EXCITATIONS IN LIQUID HELIUM*

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It has long been known that boundary effects can influence appreciably the behavior of superfluid helium. In the unsaturated helium film, in which one dimension is restricted to less than ~100 Å, the superfluid transition temperature is depressed below that of the bulk liquid,[1] and the maximum in the specific-heat anomaly also occurs at lower temperatures, and becomes smeared.[2] The measurements appeared to show that for a given film thickness the onset temperature for superflow was well below that of the specific-heat maximum by as much as 0.4°K, although in the bulk liquid the two temperatures coincide. This observation received little attention, and a later experiment[3] showed that in very fine channels of diameter approximately 70 Å the two temperatures were the same (~2.05°K) to within ±0.05°K. We have now examined this problem experimentally in some detail, and we conclude that the above results are all essentially correct, and are consistent with the presence of excitations associated with a free liquid surface, and possessing a temperature-dependent energy gap which becomes zero at a temperature lower than that where the ordered phase disappears.

The experiments consist of measuring the specific heat of helium contained within the pores of Vycor glass in the approximate temperature range 0.5 to 2.5°K with several film thicknesses, including the case where the pores are full. To interpret the results we use our previously determined absorption isotherms of helium and nitrogen on the same Vycor specimen,[4] from which we infer a pore radius of 31.2 Å, and a layer density when the pores are full summarized in the following table:

Layer	Thickness (Å)	Density [cm^3(NTP)m^{-2}]	Description
First	3.2	0.41	Solid at ~450 atm. pressure
Second	3.9	0.31	Fluid at ~35 atm. pressure
Higher		Liquid at saturation vapor pressure	Liquid at saturation vapor pressure

The first layer is found to correspond to a two-dimensional Debye solid with a specific heat $C = 0.31T^2$ Joule mole^{-1} deg^{-1}, and we assume that in view of the very large He-substrate attraction this value is independent of additional coverage. As the coverage increases above the monolayer, a weak specific-heat anomaly appears in the form of a bump which becomes sharper and moves to higher temperatures as the film thickness increases, developing eventually into the logarithmically infinite discontinuity in the bulk liquid, where the assembly size is essentially unlimited. These measurements agree with those of Frederikse[2] in a more limited temperature range.

In analyzing the results, it is convenient to subtract from the total specific heat the values for the first monolayer, and for the liquid above the second layer, and then to plot the residual specific heat logarithmically in an attempt to identify a roton-type specific heat for the second layer, which has the approximate form $C = BT^{-3/2}e^{-\Delta/kT}$, where B is a constant and Δ the roton-energy gap. For the measurements with the pores completely filled, the results of these calculations are shown in Fig. 1 as open circles. They are represented by the expression $(390 \pm 60)\exp[-(6.1 \pm 0.2)/T]$ J mole^{-1} deg^{-1}, which compares reasonably well with $520\exp(6.3/T)$ J mole^{-1} deg^{-1} obtained by extrapolating the bulk-liquid entropy data[5] to the second-layer density of 0.183 g cm^{-3}. Thus we conclude that simple size effects down to 60 Å are not important in determining the specific heat of helium II between 0.5 and 1.7°K (they must, of course, be important nearer the phase transition temperature).

However, when we attempt to analyze the lower coverage data in the same way, the result does not fit the assumption that the specific heat is the sum of contributions like those

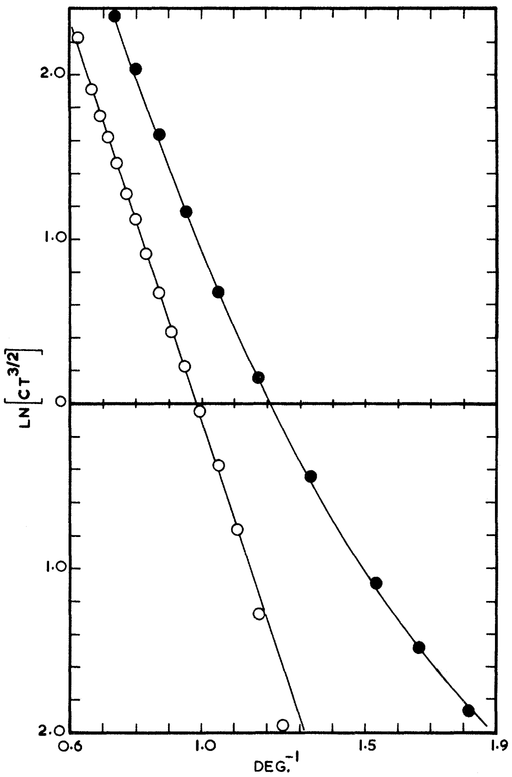

FIG. 1. Apparent specific heat of the second layer: $\ln(CT^{3/2})$ versus T^{-1}. ○, completely filled pores; ●, 75% pore filling. A roton specific heat gives a linear relationship.

in the table. Closed circles in Fig. 1 represent the apparent second-layer specific heat with a roughly 75% filling of the pores, and show that below 1°K there is a significant positive deviation from a roton-type spectrum. It seems improbable that the second-layer specific heat itself is larger, and the increase is thus presumed to be due to the presence of additional excitations. Similar results are found with other coverages, which have the common feature that the pores are not full, and hence that a free liquid surface is present. Tentatively, therefore, we ascribe this extra specific-heat contribution to surface modes, discussed by Ginsburg,[6] Kuper,[7] and Atkins and Narahara.[8] From recent surface-tension data[8] we have calculated a surface specific heat which gives order-of-magnitude agreement with this supposition.

The existence of surface excitations may explain the difference between the temperature of the specific-heat maximum and the onset temperature for superflow in a film of given thickness. Figure 2 is a log-log plot of the fractional decrease in these two temperatures as a function of the film thickness above the first solid layer. Agreement between the present and the previously obtained[2] specific-heat maxima is good, and emphasizes the large discrepancy between these temperatures and the temperatures of onset of superflow: For a given film thickness, superfluidity dies out at a well-defined temperature above which, however, the excitations contributing to the anomalous specific heat still remain until the ordered phase is destroyed. In the bulk liquid, the latter excitations are supposed to be associated with a finite energy gap, accounting for the simultaneous presence of superfluidity and an anomalous specific heat. Here, where we have a somewhat similar anomalous specific heat but no superfluidity, we may suppose that there are additional low-energy excitations present with a zero energy gap, and hence zero critical velocity, until a temperature is reached well below the specific-heat maximum, when a finite energy gap and superfluidity appear. (In a limited sense, this situation seems to be the obverse of gapless superconductivity.) Now, when the specific heat is measured in very fine

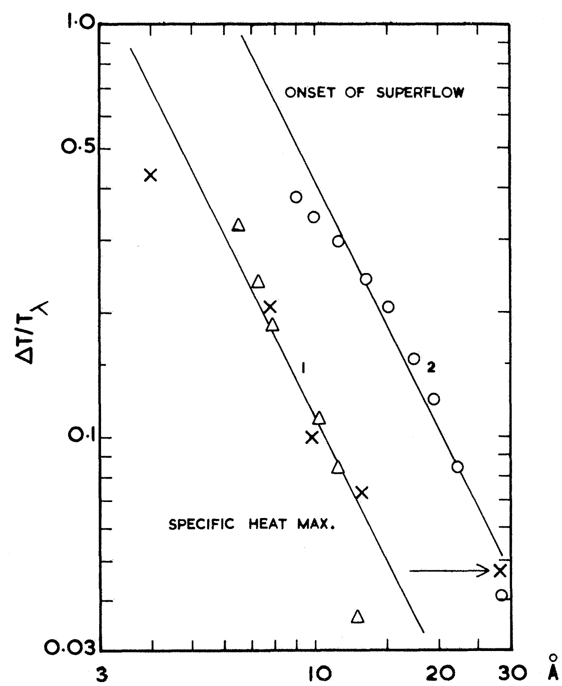

FIG. 2. Log-log plot of the fractional decrease in the temperature of the specific-heat maximum (curve 1) and onset temperature for superflow (curve 2) as a function of liquid film thickness. ○, film-flow results[1]; Δ, He^4 adsorbed on jewellers's rouge[2]; ×, present work.

pores without a free surface present, the specific-heat maximum occurs close to the temperature of onset of superfluidity, as shown by Brewer, Champeney, and Mendelssohn,[3] and confirmed by the point for full pores marked with an arrow in Fig. 2: In this case, the additional gapless surface modes are absent, and the low-temperature specific heat (Fig. 1) displays only a roton-like character. A difficulty in this interpretation of the destruction of superflow is the fact that removal of a free surface is accompanied by a lowering of the temperature of the specific-heat maximum, rather than an increase in the onset temperature for superflow which is predicted by the gapless excitation model. Further work is in progress to elucidate this problem.

The straight lines (1) and (2) in Fig. 2 are the equations

$$\Delta T = \frac{0.24\times10^{-14}}{(Z-3.2\times10^{-8})^2} \text{ (specific heat maxima)}, \quad (1)$$

$$\Delta T = \frac{0.92\times10^{-14}}{(Z-3.2\times10^{-8})^2} \text{ (superflow temperatures)}, \quad (2)$$

where Z is the total film thickness. Relations of this form have been proposed by Mendelssohn[9] and by Ginsburg and Pitaevski.[10] The latter obtained $\Delta T = 2\times10^{-14}/d^2$ for a plane film of thickness d, with the boundary condition that the order parameter $|\psi|$ vanishes at the wall and also at the film surface. With the present geometry, this condition implies that whereas with full pores $|\psi|$ need only vanish at the walls, when a free surface is present in the middle of the pores, $|\psi|$ must vanish there too.

Finally, we recognize that if surface excitations are present in liquid He^4, they should also probably occur in liquid He^3. Measurements similar to those described above, but with He^3 as adsorbate, show that size effects down to 60 Å are again unimportant in the specific heat between 0.5 and 2°K, as established with full-pore experiments; but with partial pore fillings, i.e., in the presence of free surfaces, additional contributions to the specific heat appear.

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COMBINATION SCATTERING OF MICROWAVES FROM SPACE-CHARGE WAVES IN A LABORATORY MAGNETOPLASMA*

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We report the observation of "combination" scattering[1] of microwaves from plasma waves propagating through a magnetoplasma formed in a "Q machine."[2] The measurements have been made with a radiometer which detects the microwave signal backscattered by the plasma when a low-power microwave beam is directed through the plasma parallel to the confining magnetic field. Our experimental results are in agreement with the theories of Akhiezer, Prokhoda, and Sitenko[1] and others,[3-6] who have examined "combination" scattering in unbounded gaseous plasmas, when these theories are modified to allow for geometry-dependent space-charge oscillation modes which occur in our laboratory apparatus.