Observation of mass flux through hcp $^4$He off the melting curve

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Abstract. Solid hcp $^4$He has been created off the melting curve using two growth techniques. In an effort to observe the flow of $^4$He through the solid, rather than squeezing the solid directly, the experimental apparatus allows injection of $^4$He atoms from superfluid in porous Vycor directly into the solid. We will describe the apparatus and our observations. Evidence for the transport of mass through a sample cell filled with hcp solid $^4$He off the melting curve is found. The temperature and pressure dependence of this behavior will be presented.

1. introduction

Torsional oscillator experiments on hcp $^4$He by Kim and Chan[1, 2, 3, 4] showed a reduction in the period of their oscillators as a function of temperature at temperatures below $T \approx 250$ mK. Interpreted as evidence for the presence of “supersolid” behavior in hcp solid $^4$He, their work has stimulated a great deal of interest. Efforts to observe mass flow directly[5, 6, 7] showed no evidence for such flow in solid helium. Sasaki et al.[8, 9] have concluded that preliminary evidence for flow on the melting curve was likely due to small liquid regions at the interface between crystal faces and the surface of the sample cell. Here we report evidence for flow through a cell that contains hcp $^4$He off the melting curve[10].

2. Experiment and results

We have created an apparatus, related to our “sandwich”[11] design, in an attempt to study hcp solid $^4$He at pressures off the melting curve in a way that would allow a chemical potential gradient to be applied across the solid, but not by squeezing the hcp solid lattice directly. Instead, we inject helium atoms into the solid from the superfluid. We do so by confining solid $^4$He between two Vycor plugs, each containing superfluid $^4$He. Helium is known to remain a superfluid in Vycor (and other porous materials) at pressures as high as 10 bar above the bulk $^4$He solidification pressure[?, ?, ?].

Our experimental apparatus (inset, Fig. 1) has been described in more detail elsewhere[10, ?]. Three fill lines lead to a copper cell; two with no heat sink below 4K enter via liquid reservoirs, R1 and R2, atop the Vycor (1 and 2) and a third (3), heat sunk at 1K, leads directly to the cell bypassing the Vycor. The concept of the measurement is straightforward: (a) Create a solid sample Shcp and then (b) inject (or remove) atoms into (from) the solid Shcp by feeding (removing) atoms via line 1 or 2 by an increase (decrease) in the pressure in one of those lines. We also have capacitive pressure gauges on the sample cell, C1 and C2, and can measure the
pressure of the solid *in situ*. The helium in the Vycor, in the liquid reservoirs atop the Vycor, and in the lines that feed the Vycor is maintained as a liquid by creating a temperature gradient between R1, R2 and Shcp across the Vycor by means of heaters in the vicinity of R1 and R2.

To study solid helium (using ultra-high purity helium, assumed to have $\sim 300$ ppb $^3$He) we have used two approaches: (1) grow from the superfluid with an increase in pressure at fixed temperature, or (2) grow via a modified blocked capillary technique. Evidence for the flow of mass through the solid is present (for low pressure, off the melting curve) independent of the growth technique used[10]. To date our measurements have been limited to $T \geq 360$ mK due to excess thermal conductance along the Vycor rods.

Examples of data in situations that show flow or no flow are shown in Figure 1. Here P1 and P2 are the pressures measured in the fill lines, and C1 and C2 are the pressures recorded on the capacitive gauges located on the experimental cell. The upper graph shows an example that we interpret as a demonstration of the absence of flow. A sample was created at $\approx 810$ mK followed by a change in the pressure in line 1 of $\approx 1$ bar, and after transient behavior, no degradation in P1-P2 was seen over many hours. The lower graph shows an example that we interpret as evidence for the presence of flow. In this case ($T \approx 360$ mK) pressure was increased in line 1 at $t = 20$ minutes and atoms were fed into the line until $t = 80$ minutes. Note that the increase of P2 with time is nearly linear, independent of P1-P2. The nearly linear trend is also seen in the capacitive pressure signatures, C1 and C2. We take this and other examples of data like it as evidence for superflow at a limiting velocity through the region of the cell that contains hcp solid $^4$He.

3. discussion

We have made a number of observations[10] on more than twenty five solid helium samples. (1) Generally lower pressures and temperatures show evidence for flow, higher pressures and temperatures show no evidence for flow. (2) If a sample at low temperature ($\sim 400$ mK) shows evidence for flow (by injection), and the sample is warmed to 600 mK or 800 mK, it will no longer show flow. (3) If that same sample is cooled to 400 mK injection will not show flow, but subtraction will typically show flow, as will subsequent injections. (4) A sample created fresh at 600 mK, or 800 mK, does not show flow, by injection or subtraction; (5) The lower the pressure and temperature the higher the flow rate, when flow is observed (Fig. 2).

We interpret the absence of flow for samples warmed to or created at 600 mK and 800 mK to likely rule out liquid channels of the sort discussed by Sasaki et al.[9] as the conduction mechanism. We doubt that annealing explains the behavior of these samples. Instead we suspect that whatever conducts the flow (perhaps grain boundaries or other defects) allows a flux that is temperature dependent. Sample history may also be important as shown by the warming and cooling experiments.

The measurements of Greywall and Day and Beamish, conducted at lower temperatures and higher pressures, saw no flow[5, 6, 7]. We note that there is a conceptual difference between the experiments: These previous experiments pushed on the solid helium lattice; we inject atoms from the superfluid (which must also have been the case for the experiments of Sasaki et al.[8], on the melting curve). If predictions of superflow along structures in the solid[8, 9, 10] (e.g. dislocations of various sorts or grain boundaries) are correct, it is possible that by injecting atoms from the superfluid we can access these defects at their ends in a way that applying mechanical pressure to the lattice does not allow.

Our conclusion is that helium is able to move through a region of hcp solid $^4$He, while the solid is off the melting curve, and that this flow can sometimes appear to be at a limiting velocity, consistent with superflow. We have yet to establish the true origin of this flow or what, if any, connection there may be between our observations and the torsional oscillator work done by others a lower temperatures.
Figure 1. (a) An example that shows the absence of flow. (b) An example that shows the presence of flow. Note that it is possible for the solid to support a pressure gradient in the presence of a flow.
Figure 2. Flow characteristics vs. temperature and pressure. On the vertical axis is shown \((dP_2/dt)/(P_1-P_2)\) (at the midpoint of a flow) vs. temperature, \(T\) and the cell pressure, \(P\).

We thank B. Svistunov and N. Prokofev for illuminating discussions, which motivated us to design this experiment. We also thank S. Balibar and J. Beamish for very helpful discussions and advice on the growth of solid helium, M.C.W. Chan, R.A. Guyer, H. Kojima, W.J. Mullin, J.D. Reppy, E. Rudavskii and Ye. Vekhov for discussions. This work was supported by NSF DMR 06-50092, CDRF 2853 and University Research Trust Funds.

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