Delayed Thermal Relaxation of Superfluid ^{4}He at mK Temperatures

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Abstract

It is found that the thermal relaxation of superfluid ^{4}He in the mK range differs substantially, depending on whether it has been heated with an oscillating grid or by the passage of a field emission current.

Key words: superfluid; ions; turbulence;

1. Introduction

We describe some unexpected observations made in the course of research on the decay of vorticity in superfluid ^{4}He at milli-Kelvin temperatures [1]. The latter studies show that the forced vibration of a grid in superfluid ^{4}He creates a tangle of vorticity capable of trapping negative ions. We have observed that the oscillation of the grid also causes heating of the liquid. This paper describes some preliminary measurements of this heating effect, and of the subsequent cooling of the liquid back towards its starting temperature when the driving force is removed. We also discuss the strikingly different cooling dynamics seen when, instead, the liquid is heated with a field emission current.

2. Experimental details

The apparatus consists of a cell containing $\sim$1.5 ℓ of isotopically pure ^{4}He, cooled by an Oxford Instruments Kelvinox 100 dilution refrigerator. Within the cell are a number of electrodes, the ones used for this experiment being two 1 mm thick brass plates approximately 2 mm apart, between which is placed a tightly-stretched, circular, nickel grid [2].

An AC signal from an HP3325B signal generator is applied to the upper plate for a fixed period of time, with the grid held at a high DC potential. The oscillating electric field between the two causes the grid to vibrate. The amplitude of vibration, and its phase relative to the driving frequency, can be observed by picking up the signal induced on the lower plate.

By variation of the frequency of the AC driving signal to the top electrode, a narrow resonance of width $\sim$1Hz can be detected. In the absence of damping, the amplitude of the grid's oscillations increases until it starts creating/stretching quantized vorticity in its immediate vicinity. The decay of this vorticity into thermal excitations can apparently be observed by at least two indirect methods: first, as described earlier [1], through measurement of the attentuation of negative ion signals caused by trapping of ions on the vortex lines; and secondly by observation of temperature changes within the cell, as reported below. Starting from a fixed initial temperature, the AC potential is applied for a short period of time. Subsequently, the temperature of the liquid in the cell is monitored. Thermometry consists of a 500Ω Speer carbon resistor, immersed in the superfluid, calibrated against a ruthenium oxide thermometer situated on the mixing chamber plate. The carbon resistor is in good contact with the liquid via some silver sinter bonded to one lead.

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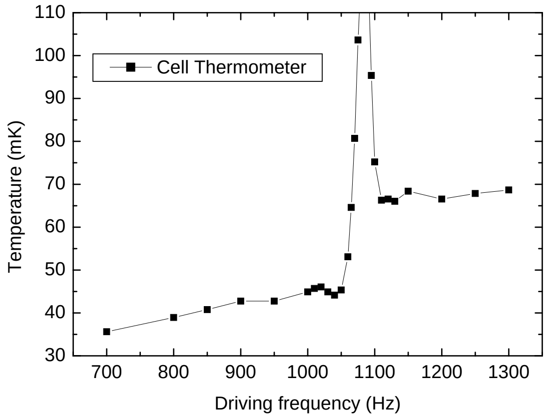

Fig. 1. Temperature rise of the ^{4}He sample as a function of the frequency of the driving force applied to the grid. The curve is a guide to the eye.

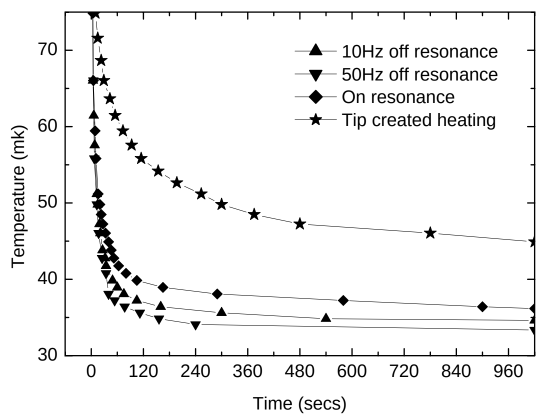

Fig. 2. Plot of cell temperature with time after energizing the grid at three different frequencies: 1082.8; 1092.8; and 1132.8 Hz. Also shown, for comparison, is a plot of cell temperature with time after heating the cell with an ion current. The curves are guides to the eye.

3. Results

Fig. 1 shows the temperature rise in the cell as a function of frequency after the grid has been driven for 120 s with 13 V peak-to-peak AC. Fig 2 shows the return to equilibrium after the cell has been heated from a starting temperature of 34.1 mK: with 300V on the grid, 5.4V AC was maintained until the cell had reached 83 mK; and the return to equilibrium was then recorded (lower theree curves) as a function of time. We also heated the cell by a different method, using a field emission tip energised at 1.5kV DC, for approximately 1 minute, switching it off when we observed that the temperature had reached 83 mK, and again followed the return to equilibrium (top curve in Fig. 2).

The curves in Fig. 2 are strongly non-exponential. To characterize the decays, we note that the times taken to cool half-way back to the equilibrium value were 12$\pm$1 s when the sample was heated with the oscillating grid, but 104.5$\pm$5 s when heated with the ion current.

4. Discussion and Conclusion

It seems likely that the the rate of cooling after oscillating the grid is influenced by vortex heating [3] as the quantized turbulence decays, but we cannot yet separate this effect reliably from the other thermal time constants in the system. The slower rate of cooling after heating to the same temperature by field emission must relate to some correspondingly slower evolution of heat within the cell. Although the majority of the ions travel at the Landau critical velocity [4], it is also possible that metastable excited states – ions or neutral molecules [5] – may be created, and that these may decay over the timescale observed to provide a continuing heat source within the liquid. One implication is that the long signal recovery times following over-driving of the field emitter [4] may relate to metastables, and not to vortices as was assumed.

In conclusion, these preliminary measurements indicate a *resonant* heating effect, attributable to the rate at which the oscillating grid creates quantized vortices. We have observed two time constants, differing by an order of magnitude, for the recovery of thermal equilibrium after the sample has been heated above the temperature of the mixing chamber. The faster one may be influenced by vortex heating [3]. The slower timescale, following field emission heating, indicates an energetic heat source persisting for many minutes, possibly associated with metastable excited states [5] in the liquid.

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