Measurement of the SOC state heat capacity in ^{4}He

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Abstract. When a heat flux Q is applied downward through a sample of liquid ^{4}He near the lambda transition, the helium self organizes such that the gradient in temperature matches the gravity induced gradient in T_λ. All the helium in the sample is then at the same reduced temperature $t_{\mathrm{SOC}} = \frac{T_{\mathrm{SOC}} - T_\lambda}{T_\lambda}$ and the helium is said to be in the Self-Organized Critical (SOC) state.

We have made preliminary measurements of the ^{4}He SOC state heat capacity $C_{\nabla T}(T(Q))$. Despite having a cell height of 2.54 cm, our results show no difference between $C_{\nabla T}$ and the zero-gravity ^{4}He heat capacity results of the Lambda Point Experiment [1] over the range 250 to 450 nK below the transition. There is no gravity rounding because the entire sample is at the same reduced temperature $t_{\mathrm{SOC}}(Q)$. Closer to T_λ, the SOC heat capacity falls slightly below LPE, reaching a maximum at approximately 50 nK below T_λ, in agreement with theoretical predictions [2].

Keywords: Self-Organized Criticality, Heat Capacity, Helium, Superfluidity
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INTRODUCTION

In 1987, the Self-Organized Critical (SOC) state was predicted for the normal phase of ^{4}He in the presence of gravity [3]. Gravity creates a hydrostatic pressure gradient in the helium which creates a gradient in T_λ, the superfluid transition temperature, of $\nabla T_\lambda = 1.273\ \mu\mathrm{K/cm}$ [4]. The thermal conductivity $\kappa(t)$, where $t = \frac{T - T_\lambda}{T_\lambda}$, diverges as $t \to 0$[1]. When a heat flux Q is applied downward through a sample of helium, the resulting temperature gradient parallels the gradient in T_λ, and the helium self organizes to satisfy the condition $Q/\kappa = \nabla T_\lambda$. Therefore, while there is a gradient in temperature, the temperature difference from T_λ is uniform for the entire sample, as shown in Fig. 1.

The SOC state in ^{4}He was first observed in 1997 by Moeur *et al*. [5]. They saw not only the expected normal phase SOC state, but also, for higher heat fluxes, self organization at temperatures below T_λ. They found that κ diverged not at T_λ, but at $T_{\mathrm{DAS}}(Q)$, where $T_{\mathrm{DAS}}(Q)$ is the measured temperature, under a heat flux Q, at which perfect thermal conductivity of the superfluid state fails abruptly in experiments where the heat flux is applied upwards through the helium [6]. This encouraged the interpretation that the heat flux was depressing the critical point T_λ to the lower $T_\lambda(Q) = T_{\mathrm{DAS}}(Q)$ and that the SOC state was always on the 'normal' side of T_λ. In contrast, Weichman and Miller presented a theoretical model in one dimension that treated the high heat flux self organization as a superfluid with a series of phase slips in order to maintain the requisite temperature gradient [7].

In this paper, we report the first measurements of the heat capacity of the SOC state[2].

EXPERIMENT

Our cell is constructed with two 2.3 cm diameter gold plated copper endplates epoxied to a cylindrical insulating Vespel® sidewall in order to give a 2.54 cm sample height. We have three high resolution thermometers (HRTs); one on each of the top and bottom endplates and a third on a 165 μm thick copper foil which penetrates the sidewall. This foil is positioned 0.64 cm above the bottom endplate and is in direct contact with the helium sample.

Since the temperature of the SOC state is determined by the heat flux through the helium, one cannot put in a pulse of energy and measure the temperature change as in a conventional heat capacity measurement. Instead, the heat capacity is measured by establishing the SOC state throughout the sample at one heat flux, then switching to a new heat flux, and then measuring the amount of energy needed to re-establish the SOC state throughout the sample at its new temperature. This is shown schematically in Fig. 1.

In traditional helium heat capacity measurements, where the helium is isothermal, the gradient in T_λ causes

[1] Note: this is true only in the small Q limit.

[2] Note, these measurements are very different from previous work [8] on the SOC/superfluid two-phase heat capacity.

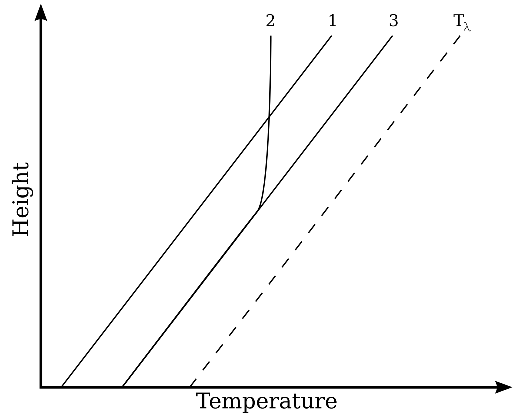

FIGURE 1. Profiles of the helium temperature vs. sample height during the experimental procedure: (1) The SOC state is fully established at the first heat flux; (2) The heat flux has been decreased which raises the SOC temperature; (3) Energy is added to fully establish the SOC state for the second heat flux. (Note, for $Q \lesssim 100$ nW/cm^2, the helium self organizes above T_λ.)

the heat capacity to be gravity rounded, (i.e. averaged over a range of reduced temperatures.) In contrast, in the SOC state, the temperature gradient is equal to ∇T_λ and the entire sample is equidistant from criticality. Therefore, there is no gravity rounding in our data, despite having a sample height of 2.54 cm. Our SOC heat capacity results shown in Fig. 2 are compared directly to a fit of the LPE results. Haussmann's prediction for the SOC heat capacity using Dynamic Renormalization Group (DRG) theory is also plotted [2].

In addition, we also measured the self-organization temperature versus heat flux. Our results for heat fluxes in the range of 0.5 to 4.5 μW/cm^2 are well fit by the formula $t_{\mathrm{SOC}}(Q) = -(Q/Q_0)^{0.813}$ with $Q_0 = 760 \pm 10$ W/cm^2. This measurement differs significantly from that first reported by Moeur *et al.* [5], but agrees well with a later experiment [8].

CONCLUSIONS

Our data in Fig. 2 show no measurable difference from the LPE results in the range 250 to 450 nK below T_λ - i.e. the SOC state heat capacity is the same as that for the static superfluid. This may imply that the helium of the SOC state, in this heat flux range, is essentially in the superfluid phase. If so, this clearly rebuts arguments that $T_{\mathrm{DAS}}(Q)$ is a depressed critical point, despite the fact that the thermal conductivity κ diverges at this temperature.

Closer to T_λ, we measured a slight depression in the heat capacity, relative to LPE, which starts at approximately 250 nK below the transition. This differs from

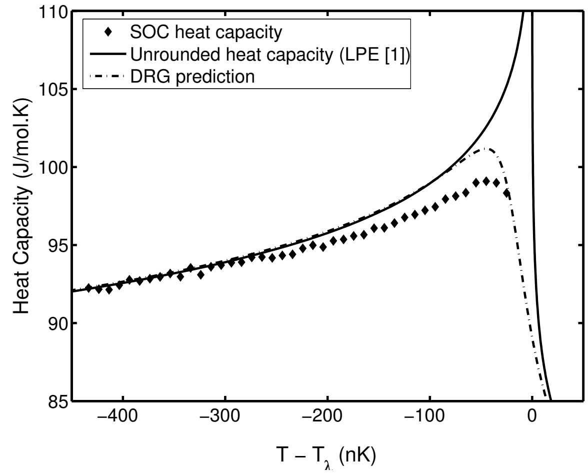

FIGURE 2. Heat capacity of the SOC state

the prediction of the DRG theory, where the depression starts at approximately 100 nK below T_λ [2]. However, both theory and experiment reach a maximum at approximately 50 nK below T_λ.

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