HTML ABSTRACT + LINKS

Measurement of the SOC State Specific Heat 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 specific heat, $C_{\nabla T}(T(Q))$. Despite having a cell height of 2.54 cm, our results show no difference between $C_{\nabla T}$ and the zero-gravity ^{4}He specific heat results of the Lambda Point Experiment (LPE) [J.A. Lipa et al., *Phys. Rev. B*, **68**, 174518 (2003)] 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 specific heat falls slightly below LPE, reaching a maximum at approximately 50 nK below T_λ, in agreement with theoretical predictions [R. Haussmann, *Phys. Rev. B*, **60**, 12349 (1999)].

Keywords: Self-Organized Criticality, Specific Heat, Helium, Superfluidity
PACS: 65.20+w,67.40.Kh,05.65+b

INTRODUCTION

In 1987, the Self-Organized Critical (SOC) state was predicted for the normal phase of ^{4}He in the presence of gravity [1]. Gravity creates a hydrostatic pressure gradient in the helium which creates a gradient in T_λ, the superfluid transition temperature, of $\nabla T_\lambda = 1.273\ \mu\mathrm{K/cm}$ [2]. The thermal conductivity $\kappa(t)$, where $t = \frac{T - T_\lambda}{T_\lambda}$, diverges as $t \to 0$ [3]. 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 throughout the entire sample, as shown in Fig. 1.

The SOC state in ^{4}He was first observed in 1997 by Moeur *et al*. [4]. They saw not only the expected normal phase SOC state, but also self-organization at temperatures below T_λ at higher heat flux. In addition, they found that κ diverged at $T_{\mathrm{DAS}}(Q)$, where $T_{\mathrm{DAS}}(Q)$ is the measured temperature at which perfect thermal conductivity of the superfluid state fails abruptly under a heat flux Q applied upwards through the helium [5]. 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 therefore 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 [6].

In this paper, we report the first measurements of the specific heat of the SOC state [7].

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 that penetrates the sidewall. This foil is positioned 0.64 cm above the bottom endplate and is in direct contact with the helium sample. We measured the size of our helium sample (0.389 moles) through a calibrated extraction and confirmed it with a traditional pulse heat capacity measurement in the superfluid phase.

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 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. As heat is slowly added, the derivative of the top endplate thermometer is used to find the time when profiles 1 and 3 are reached, while the midplane thermometer measures the SOC temperature change.

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman
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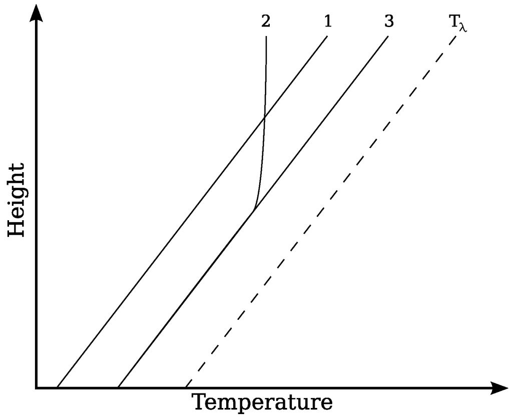

FIGURE 1. Profiles of helium temperature vs. sample height during the experimental procedure: (1) SOC state is fully established at the first heat flux; (2) Heat flux is decreased which raises the SOC temperature; (3) Energy is added to fully establish SOC state for the second heat flux. (Note: for $Q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

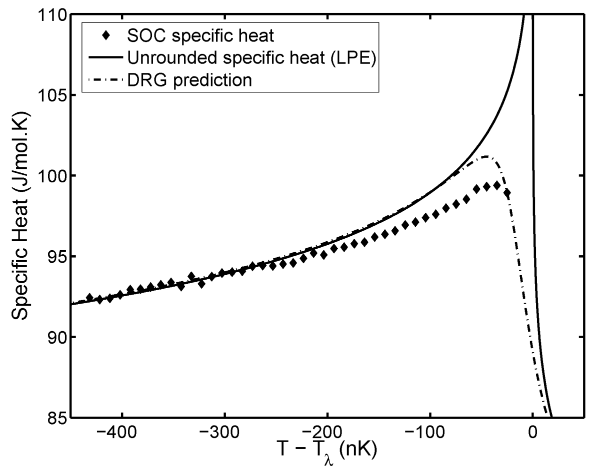

FIGURE 2. Specific heat of the SOC state

In traditional helium heat capacity measurements, where the helium is isothermal, the gradient in T_λ causes 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 a sample height of 2.54 cm. Our SOC specific heat results shown in Fig. 2 are compared directly to a fit of the Lambda Point Experiment (LPE) results [8]. Haussmann's prediction for the SOC specific heat using Dynamic Renormalization Group (DRG) theory is also plotted [9].

We also measured the SOC temperature versus heat flux. Our results for 0.5 to 4.5 $\mu\mathrm{W/cm^2}$ are well fit by $t_{\mathrm{SOC}}(Q) = -(Q/Q_0)^{0.813}$ with $Q_0 = 760 \pm 10\ \mathrm{W/cm^2}$. Our Q_0 differs from Moeur *et al.* [4], but agrees well with a later experiment [10].

CONCLUSIONS

The 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 in this heat flux range of the SOC state is essentially in the superfluid phase. If so, this 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 measure a slight depression in the specific heat, relative to LPE, which starts at approximately 250 nK below the transition. This differs from the prediction of the DRG theory, where the depression starts at approximately 100 nK below T_λ [9]. However, both theory and experiment reach a maximum at approximately 50 nK below T_λ.

ACKNOWLEDGMENTS

We would like to thank Dmitri Sergatskov, Steve Boyd, Alex Babkin, Alexander Churilov, and Talso Chui for helpful discussions and assistance with cell construction and cryovalve assembly and operation. This work was supported in part by the Fundamental Physics Discipline of the Microgravity Science Office of NASA.

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