Simulated avalanches in the draining of superfluid helium from Nuclepore

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Abstract

Superfluid ^{4}He exhibits hysteretic behavior in the percolated material Nuclepore during filling and draining of the pores due to capillary condensation, and one observes avalanches in the pore draining within a narrow range of chemical potential. We have previously demonstrated that the avalanches involve pores distributed across the entire sample, and that the avalanches are enabled by the superfluid film. We have simulated avalanches in Nuclepore, and the statistics of our simulated avalanches show similarities to the observed statistics of avalanches in Nuclepore when fluid flow off of the substrate is unimpeded.

Key words: superfluid helium; porous material; avalanches; simulations

1. Introduction

When superfluid ^{4}He is capillary condensed in and then subsequently drained from Nuclepore, a porous membrane with intersecting pores, one observes hysteretic behavior and avalanches during the draining of the pores. These avalanches are the result of many interacting pores draining in discrete coordinated events, and they involve pores distributed across the entire sample. We have shown previously [1] that the statistics of the avalanches depends on the physical interconnections of the pores and the presence of a superfluid film connection among them. We have also shown that the statistical nature of the avalanches depends on whether the fluid flow off the Nuclepore substrate is unimpeded [2]. In the work we report here we have simulated avalanches on Nuclepore for the case where fluid flow off the substrate is unimpeded, and we compare our simulated results to our experimental results for unimpeded flow [2].

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2. Experimental Results

Nuclepore is a 10 μm thick polycarbonate material that has a random spatial distribution of nearly cylindrical pores of nominal diameter 200 nm. It has a pore density of $\psi_N = 3.5$ x 10^8 pores/cm^2, and a random tilt angle, θ, of the axis of each pore from the normal to the surface, $0^\circ \leq \theta \leq 34^\circ$. These parameters lead to a large number of intersections among the pores in the sample.

The amount of superfluid ^{4}He in the pores of Nuclepore is measured using a capacitance technique. We measure the amount of fluid in the pores as a function of chemical potential by taking alternating capacitance measurements and third sound velocity measurements. The details of the experimental setup and these measurements are explained more completely elsewhere [1]. A plot of $C_{fraction}$, the fraction of fluid remaining in the pores, as a function of chemical potential μ(K) for filling and draining pores is seen in Fig. 1. Note that half of the pores drain during a narrow range of chemical potential (inset box). It is within this range of draining that we observe avalanches. Fig. 2 shows a log-log plot of avalanche size s as a function of $C_{fraction}$.

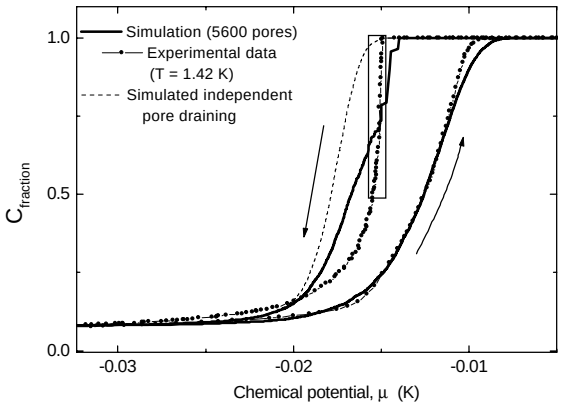

Fig. 1. Fraction of fluid remaining in the pores, $C_{fraction} = \frac{C - C_{empty}}{C_{full} - C_{empty}}$, as a function of chemical potential μ (K) for a simulation with 5600 pores, actual data, and independent pore draining. The box on the experimental data indicates the region of draining over which we observe avalanches.

3. Simulations and Discussion

To simulate avalanches in Nuclepore, we model the connectivity of the pores and the filling and draining of the pores. Our model used 5600 pores, randomly laid down on a surface, with a random azimuthal angle ϕ and a normal tilt angle of θ ($0^\circ \leq \theta \leq 34^\circ$) assigned to each pore. The pores of Nuclepore are barrel shaped; the average internal diameter is ≈240 nm ±20%. The average diameter at the surface of the membrane is 180 nm, with 200 nm as an upper limit. We assigned an internal radius and surface radius to each pore. In calculating the connectivity of the pores we found that each pore intersected with an average of 6.5 other pores. Since connection only matters here if fluid can flow through the intersection, we considered two pores "connected" if the distance of closest approach between their two axes was less than half the sum of the two radii. Using this criterion, we calculated that each pore was connected to an average of 3.2 other pores, well within the percolation limit.

The chemical potential at which a pore will capillary condense is determined by its internal diameter, but the chemical potential at which a pore will drain is determined by the diameter of the pore at the membrane surface. We assigned filling(draining) chemical potentials as a function of internal(surface) diameters according to the functions given by Cohen, Guyer, and Machta [3]. We assigned internal diameters so that our simulated adsorption curve would fit the data curve in Fig. 1. To accomplish this required an average internal diameter of 240 ± 43 nm, and an average surface diameter of 180 ± 18 nm.

We drained our simulated pores in clusters, which are the avalanches. A cluster of pores is determined by first identifying the undrained pore with the largest surface diameter, d_{top}. This is the pore through which the fluid from the cluster of pores will drain. We then look at all pores connected to it. In order for a pore to be part of the cluster, its internal diameter must be larger or equal to d_{top}, and there must be a path through other pores which meet the same criterion to the draining pore. The results of our simulation are seen in Fig. 2, and they are qualitatively similar to experimental results thus establishing the importance of pore-pore intersections.

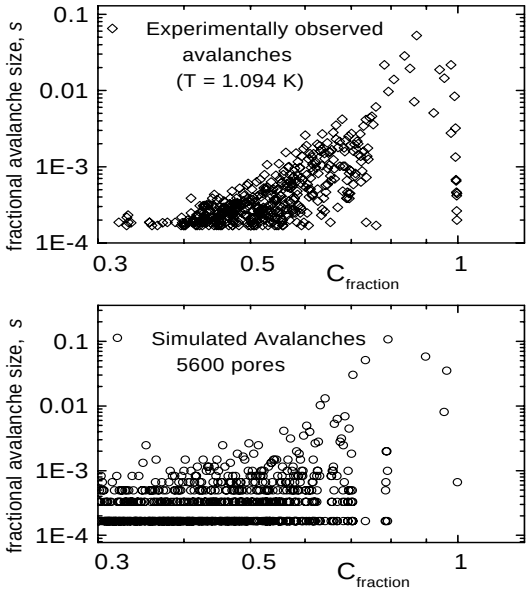

Fig. 2. Experimental and simulated plots of fractional avalanche size, $s = \Delta C/(C_{full} - C_{empty})$ as a function of fraction of fluid remaining in the pores, $C_{fraction}$.

Acknowledgements

We thank Robert Guyer for helpful discussions. This work was supported by the National Science Foundation through DMR 98-19122 and DMR 01-38009.

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