Superfluid Density of $^4$He Films Adsorbed in Porous MCM–41 Ceramic

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The superfluid transition of $^4$He films adsorbed in MCM-41 ceramic with 40-A-diameter, micron-length cylindrical channels is studied with a torsion oscillator technique. For film coverages above 1.7 layers a finite-size Kosterlitz-Thouless transition becomes apparent in the data, with considerable broadening of the KT jump of the superfluid fraction. With decreasing helium coverage the extent of the broadening increases, indicating that the vortex core size is increasing. The data is consistent with the Machta-Guyer theory of the KT transition in a cylindrical channel, but with a coverage–dependent vortex core size. At low temperatures a linear decrease of the superfluid fraction with temperature is observed, indicating a zero-dimensional excitation. PACS numbers: 67.40.Db, 67.40Rp, 67.40.Vs, 67.40.Hf

1. INTRODUCTION

Superfluid $^4$He films adsorbed in porous substrates have been studied extensively in the past decades to probe the dimensionality properties of superfluidity. Films adsorbed on a flat two-dimensional substrate show a Kosterlitz-Thouless (KT) phase transition, with a sharp jump to zero of the superfluid density at the transition temperature $T_{KT}$ corresponding to the unbinding of vortex-antivortex pairs$^3$. The phase transition of films adsorbed in porous substrates, such as porous Vycor glass and packed powders, exhibits a much more broadened KT transition. This has a simple interpretation as a finite-size KT phase transition$^2$–$^4$, in which the KT recursion relations have a finite-length cutoff introduced due to the pore size of the substrates$^5$–$^9$. These studies found a substantial increase in the broadening of the transition as the film became thinner, which could be explained as an increase in the vortex core size when the superfluid thickness of the film
became less than an atomic layer\textsuperscript{4,9}. In this paper, we present a study of superfluid phase transitions of helium films adsorbed in MCM-41 ceramic with 40-Å-diameter, micron-length channels. The superfluid density is measured with a torsion oscillator technique. Superfluidity is observed in films thicker than 19.8 $\mu$ mole/m$^2$ (1.7 atomic layers), and the phase transitions of the films thicker than 22.6 $\mu$ mole/m$^2$ (2.0 layers) display the characteristics of broadened finite-size KT transitions. The data is consistent with the Machta-Guyer\textsuperscript{7} theory of the KT transition in a cylindrical geometry, if the vortex core size is taken to be coverage-dependent. In addition, we observe a linear temperature dependence of the superfluid density at low temperatures. This is the signature of zero-dimensional excitations, which are possibly third sound modes propagating in the azimuthal direction of the channel.

2. Experimental Method

The experiment is carried out using a torsion oscillator technique at a frequency of 1.7 kHz. The MCM-41 ceramic powder is mixed with 1-micron silver powder in a 10:1 weight ratio to improve the thermal conductivity at low temperature and to increase the stability of the packing. The powder is packed into the sample cell with pressures of 200–400 psi, which is low enough to avoid collapsing the mesopores. The substrate is then degassed at 120 °C for 16 hours. A computer-controlled dilution refrigerator is used for