Superfluidity of ^{4}He film adsorbed on 47 Å pores

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Abstract

The superfluid of ^{4}He films adsorbed on uniform straight pores 47 Å in diameter has been studied using a torsional oscillator in order to investigate the nature of the superfluid transition of the film formed in several nanometer pores. The results show that the film in the pore is certainly superfluid above 1.5 layers. The temperature dependence of the superfluid density below the superfluid transition temperature is not so sharp compared with that expected by the Kosterlitz-Thouless transition. This behavior is qualitatively explained by the strong confinement of the vortex pair.

Key words: low dimensional; Bose-Einstein condensation; Kosterlitz-Thouless transition

1. Introduction

The dimension of the system has a significant influence on the nature of Bose fluid. In two-dimensional (2D) system, the superfluid of the ^{4}He film occurs via the Kosterlitz-Thouless (KT) mechanism due to the unbinding of the vortex-antivortex pair. One-dimensional (1D) ^{4}He Bose fluid was realized recently by ^{4}He film adsorbed on the wall of the uniform pore 18 Å in diameter[1]. In this system the phonon can be excited only along the channel, causing the linear temperature dependent heat capacity at low temperature. When the pore diameter (d) is increased, the film will gain 2D properties, and become complete 2D system in an infinite diameter. It is very interesting to investigate how the properties of the Bose fluid evolves from 1D to 2D with increasing the pore size. In this article we present the results of the torsional oscillator experiment of ^{4}He film adsorbed on the uniform pores 47 Å in diameter.

2. Experimental

The substrate used in this work is FSM[2], a family of highly ordered mesoporous silica crystals with regular arrangement of uniform hexagonal channels as shown in Fig. 1(a) inset. This material has a remarkable feature that the pore size can be controlled between 15 Å and 50 Å precisely in the syntheses process. In this work, we used FSM with pores 47 Å in diameter. The substrate is in a form of powder with a particle size of about 0.3 μm. It was mixed with silver powder in a 2:1 weight ratio, pressed onto a torsion head, and dehydrated in a vacuum at 170 °C. Surface area (S) was 135 m^2 determined by the BET fitting of an N_2 adsorption isotherm at 77 K between 0.05 and 0.22 mbar. The area outside the powder is less than 1 % of the total surface area estimated from the powder size of FSM. The torsion rod was made of Al alloy 5056 with a quality factor (Q) of 1.3×10^6. The torsional oscillator has a resonant frequency of 1106 Hz.

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3. Results and Discussion

A typical set of observed superfluid signatures of the film adsorbed on 47 Å-pores is shown in Fig. 1, where the frequency shift (ΔF) and the dissipation change (ΔQ^{-1}) of the oscillator caused by the superfluid transition are plotted. With decreasing temperature, $2\Delta F/F$, which is proportional to the superfluid density ($\rho_s(T)$), shows a gradual increase below a superfluid onset temperature (T_{on}) arising from the superfluid film decoupling from the motion of the oscillator. The superfluid is observed above $n/n_1 \sim 1.5$. Here n is coverage and n_1 is the first layer completion coverage determined by the precise vapor pressure measurements using the same technique as with 18 Å substrate[3]. The detailed vapor pressure results will be described elsewhere. Extrapolation of $2\Delta F/F$ to 0 K gives us 7.2 % of the superfluid decoupling. This large decoupling ratio strongly suggests that the film in the pore is certainly superfluid, because the decoupling due to the film adsorbed on the surface outside powder is expected to be less than 1 %.

ΔQ^{-1} shows a broad peak below T_{on}. At the peak temperature the superfluid density is $0.85\rho_s(0)$. This makes a contrast with a KT transition observed with a Mylar sheet substrate, where a dissipation peak usually locates at temperature where $\rho_s(T) \sim \rho_s(0)/2$. The dissipation peak is one order of magnitude wider than that with Mylar substrate. However, the area integrated under the normalized dissipations $\rho_s^0 \mathrm{Im}[\varepsilon^{-1}(\omega)]/n$ with two substrates agree within factor of two, where $\varepsilon(\omega)$ is the dielectric constant defined in [4]. This fact suggests that the vortex pair unbinding mechanism play an important role on the superfluid transition in 47 Å pores.

In Fig. 1(a), the temperature dependence of the superfluid density is compared with Mylar substrate. On it the superfluid density shows a discontinuous jump at T_{on}. On the other hand, on 47 Å-pores the superfluid density shows the gradual temperature dependence. This can be understood by the system size dependent KT theory that only the vortex-antivortex pair separated smaller than $\pi d/2$ can unbind and destroy the phase coherence due to the cylindrical geometry[6]. This causes the increase of T_{on} and continuous evolution of the superfluid density below T_{on}.

Our conclusion that the vortex unbinding mechanism plays a significant role at the superfluid transition on 47 Å-pore has an important meaning that two characteristic behaviors are revealed on the same kind of substrates, one is the vortex mechanism on 47 Å-pore similar to the 2D system, the other is 1D behavior on 18 Å-pore[1]. The vortex mechanism will break down for the pores with diameter comparable to the vortex core diameter, which is experimentally estimated to be

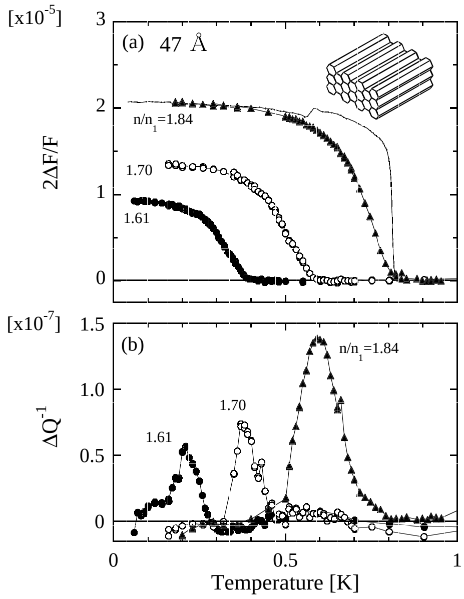

Fig. 1. (a) Frequency shift ($2\Delta F/F$) and (b) dissipation change (ΔQ^{-1}) of the torsional oscillator due to the superfluid of ^{4}He film adsorbed on 47 Å-pores. Solid line in (a) is data with Mylar substrate[5] scaled at T_{on} and $2\Delta F/F$ at 0 K.

25 ± 12 Å[7]. Thus it is quite interesting to investigate systematically how nature of the Bose fluid changes with between 18 Å and 47 Å on the FSM substrate.

4. Conclusion

We studied the superfluid of ^{4}He films adsorbed on such uniform pores 47 Å in diameter. The film is certainly superfluid above 1.5 layers. The temperature dependence of the superfluid density and dissipation shows that the vortex unbinding mechanism plays an important role at the superfluid transition.

References

[1] N. Wada, J. Taniguchi, H. Ikegami, S. Inagaki, Y. Fukshima, Phys. Rev. Lett. **86** (2001) 4322.

[2] S. Inagaki, A. Koiwai, N. Suzuki, Y. Fukushima, K. Kuroda, Bull. Chem. Soc. Jpn. **69** (1996) 1449.

[3] J. Taniguchi, T. Okuno, H. Ikegami, N. Wada, S. Inagaki, Y. Fukushima, J. Low Temp. Phys. **121** (2000) 537.

[4] V. Ambegaokar, B. Halperin, D. Nelson, E. Siggia, Phys. Rev. B **21** (1980) 1806.

[5] H. Yano, T. Jocha, N. Wada, Phys. Rev. B **60** (1999) 543.

[6] T. Minoguchi, Y. Nagaoka, Prog. theor. Phys. **80** (1988) 397.

[7] K. Shirahama, M. Kubota, S. Ogawa, N. Wada, T. Watanabe, Phys. Rev. Lett. **64** (1990) 1541.