Phonon velocity of ^{4}He Bose fluid formed in one-dimensional 18 Å-pores

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Abstract

We discuss the one-dimensional (1D) phonon velocities of ^{4}He adsorbed on straight 18-Å pores deduced from our recent two experiments, the vapor pressure and the heat capacity measurements. The heat capacity of the second layer fluid is proportional to temperature below 0.2 K, which is attributed to 1D phonon excitations along the tube. The phonon heat capacity gives us the phonon velocity, v_C. While, the phonon velocity, v_P, also can be deduced from the vapor pressure. The magnitude and coverage dependence of v_P and v_C agree well. This fact strongly supports that the temperature-linear heat capacity is the 1D phonon heat capacity.

Key words: ^{4}He film; 1D quantum fluid; phonon velocity

1. Introduction

Comparing with the three-dimensional and two-dimensional helium fluids, there were few studies about one-dimensional (1D) helium fluids. Recently ^{4}He adsorbed on the FSM[1] substrate with straight pores 18Å in diameter has been studied by the vapor pressure[2] and the heat capacity measurements[3] in order to investigate 1D ^{4}He Bose fluid. There ^{4}He atoms are adsorbed on the pore walls and form a thin film up to second layer[2]. In the second layer, the heat capacity of ^{4}He[3] differs from that of ^{3}He[4], which indicates the second layer ^{4}He is Bose fluid. The heat capacity of the second layer ^{4}He is dominated by temperature-linear term below 0.2 K. This temperature dependence is considered to be due to 1D phonon excitation, since the transverse degree of freedom is frozen out.

In this article, we deduce the phonon velocity of ^{4}He film adsorbed on 18-Å pores from two different experimental data, one is the heat capacity[3], and the other is the vapor pressure data[2]. We compared two phonon velocities and discuss the low temperature excitation of the ^{4}He film.

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2. Results and discussion

To know how the films grow on the 18 Å-pore walls, we have measured the vapor pressure, P, of the films[2]. The results indicate that the first layer is completed at $n_{1st} = 2.4$ mmol against the surface area of S =195 m^2 and that the second layer is formed on the first layer between n_{1st} and $n_{full} = 1.42n_{1st}$.

The isothermal compressibility of the second layer, κ_{T2}, can be obtained from vapor pressure isotherms by the follwing equation,

$$\kappa_{T2} = \frac{S_2}{N_2^2 T}\frac{\partial N_2}{\partial \ln P}, \qquad (1)$$

where T is the temperature, $N_2 = N_{\rm A}(n - n_{\rm 1st})$ is the number of atoms in the second layer and $N_{\rm A}$ is the Avogadro number. Here we assumed the first layer

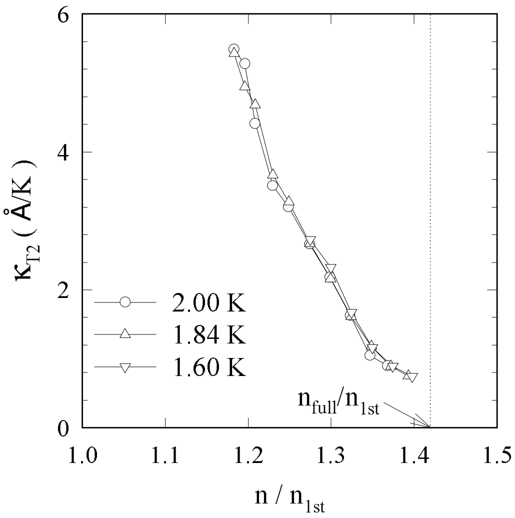

Fig. 1. 2D isothermal compressibility of the second layer at 2.00 K (○), 1.84 K (△), 1.60 K (▽). The dashed line indicates n_{full}/n_{1st}.

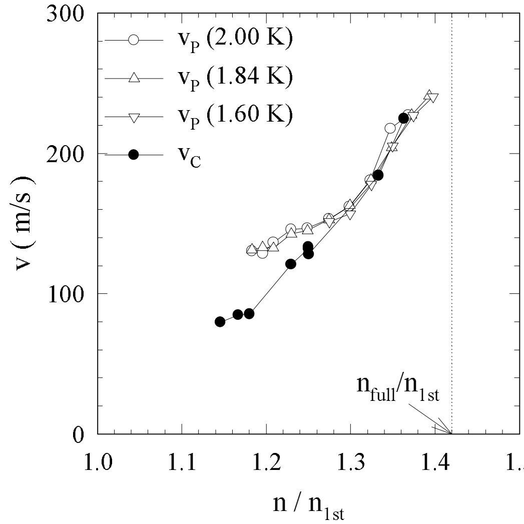

Fig. 2. Phonon velocities, v_P (open symbols) derived from vapor pressure and v_C (●) derived phonon from heat capacity[3] as a function of n_{1st}.

density does not change after the first layer completion. S_2 is the surface area for second layer atoms to be adsorbed, which is estimated to be $195 \times (18 - 3.5 \times 2)/18 = 119$ m^2, assuming the thickness of the first layer to be 3.5 Å. The obtained κ_{T2} is shown in Fig. 1. With increasing coverage, κ_{T2} decreases due to the increase of the interaction between ^{4}He atoms.

The phonon velocity of the second layer, v_P, is related to κ_{T2} through

$$v_P = \sqrt{\frac{1}{\kappa_{S2}\rho_2}}, \tag{2}$$

where κ_{S2} is the 2D isentropic compressibility, $\rho_2 = N_2 m_4/S_2$ is the second layer density and m_4 is the mass of one ^{4}He atom. Here we assume $\kappa_{S2} = \kappa_{T2}$. The obtained v_P is shown in Fig. 2. As the coverage is increased, v_P increases. The magnitude of v_P is similar value to the bulk liquid sound velocity, typically 230 m/s. This fact supports that the second layer ^{4}He is a fluid state.

Next let's discuss the heat capacity of the second layer. It is dominated by the temperature-linear term, αT, below 0.2 K[3]. Because it is attributable to the 1D phonon excitation, the phonon velocity, v_C, is deduced from

$$v_C = \frac{2\pi^2}{3}\frac{L}{h\alpha}k_{\mathrm{B}}^2, \tag{3}$$

where $L = S_2/\pi d$ is the total 1D length of the second layer and $d = 18 - 3.5 \times 2 = 11$ Å is its diameter. v_C is also shown in Fig. 2. The magnitude and the coverage dependence of v_C and v_P agree very well. This result strongly supports that the temperature-linear term of the heat capacity is due to the 1D phonon excited in the second layer fluid ^{4}He along the channel.

3. Conclusion

We estimated the phonon velocity from two independent experiments, the heat capacity and the vapor pressure measurements. These magnitude and the coverage dependence agree well. This fact strongly suggests that the temperature-linear heat capacity of the second layer is attributed to the 1D phonon along the channel.

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