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Dynamical superfluid response of ^{4}He confined in a nanometer-size channel

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We have studied the superfluid response of liquid ^{4}He confined in a one-dimensional nanometer-size channel by means of a twofold torsional oscillator at 2000 and 500 Hz. For the lower-frequency mode, both the superfluid onset and the dissipation peak shift to the low-temperature side by 40 mK under 0.13 MPa, and the shift is slightly enhanced by the application of pressure. The strong frequency dependence indicates that the superfluid response is a dynamical phenomenon. Furthermore, this dependence is consistent with the theoretical prediction based on the Tomonaga-Luttinger liquid model.

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I. INTRODUCTION

One-dimensional (1D) quantum many-body systems have fascinated many physicists for over half a century since the work of Bethe.[1] They show physical properties different from those of higher-dimensional systems, and there exist exactly solvable models. The Tomonaga-Luttinger (TL) liquid model is one of these models, and it provides a universal description of interacting fermions at low energies.[2] The TL liquid of a 1D electron system has been realized using a carbon nanotube or a quantum wire, and various peculiar features, such as power-law anomalies for momentum distribution or conductivity, have been discovered.[3,4] Since 1D bosonic systems were also realized in ultracold atoms[5–7] and superconducting wires,[8,9] the TL liquid model has been extended to these bosonic systems.[10]

In the case of liquid ^{4}He, two systems, liquid ^{4}He confined in the 1D channel[11] and dislocation in solid ^{4}He (Ref. 12) have been thought of as candidates for bosonic TL liquids. For the latter system, Vekhov and Hallock recently measured the mass flux in solid ^{4}He, where the flux was assumed to be carried by the superfluid core of edge dislocations.[13] They found a power-law dependence on the chemical-potential difference between two reservoirs in series with the solid. It provides the first evidence of the bosonic TL liquid where the supercurrent is due to quantum phase slip.

Regarding liquid ^{4}He confined in the 1D channel, we have studied the superfluidity for several sizes of the channel[14–16] and have carried out heat-capacity measurements for 2.8 nm in diameter.[17] It was found that ^{4}He atoms enter a low-entropy state at TB of about 1.65 K under 0.03 MPa and show the superfluidity at the lower-temperature side. Under a low pressure of 0.01 MPa, the resonance frequency increases gradually at To of about 0.9 K. In addition, it was observed that the superfluid response is characteristic of a broad dissipation peak below T_o. The gradual increase in superfluid and the broad dissipation indicate the possible appearance of a 1D feature.

According to quantum Monte Carlo simulations by Del Maestro *et al.*, ^{4}He atoms confined in the 2.4-nm channel delocalize into the TL liquid with a finite superfluid fraction.[18] In addition, Eggel *et al.* calculated the momentum response of the TL liquid under the conditions of interacting with the container wall.[19] They showed that the superfluid response is essentially a dynamical phenomenon related to the suppression of quantum phase slip. Furthermore, they predicted that the dynamical aspect would be most obvious on a measuring frequency dependence of superfluid response.

To clarify the dynamical aspect of superfluidity for ^{4}He in the 2.8-nm channel, we have performed measurements by means of a twofold torsional oscillator at 2000 and 500 Hz. For the lower-frequency mode, both the superfluid growth and the dissipation peak shift to the low-temperature side by 40 mK under 0.13 MPa. The strong frequency dependence confirmed that the superfluid response is a dynamical phenomenon. The Luttinger parameter K, calculated from the frequency dependence, was found to be close to that estimated from the compressibility. It means that the observed superfluid response is consistent with the theoretical prediction based on the TL liquid model.

II. EXPERIMENTS

In the present experiments, we used a porous material, folded-sheets mesoporous material (FSM).[20] It has a honeycomb structure of a 1D uniform nanometer-size straight channel without interconnection. We adopted the same batch of material as in the previous experiments.[14,17] The 1D channel was 2.8 nm in diameter and 0.2–0.5 μm in length. FSM powder was formed into a pellet: It was mixed with silver powder, was put into a BeCu cap, and was heated under pressure of 6.3×10^3 N/cm^2 in a vacuum. The surface area of the pellet was determined to be 90 m^2 from the Brunauer-Emmet-Teller fitting to the N_2 adsorption isotherm. Its channel volume was estimated to be 70 mm^3 from the surface-volume ratio of the FSM powder.[21] In addition to the channel, there was an open space between FSM powders in the pellet.

The measurements were carried out using a twofold torsional oscillator, which has two masses, the dummy mass and the torsion head (the BeCu cap with the pellet) as shown in Fig. 1. They were connected by a torsion rod. The two torsion rods, the dummy mass and the flange of the torsion head fitted to the BeCu cap were machined from a single stock of BeCu. The oscillator has two resonance modes: The lower (f_l) one operates when the dummy mass and the torsion head move in phase, and the higher (f_h) one operates when they move in opposite phase. When liquid ^{4}He was filled at 0.13 MPa, the resonance frequency and Q factor for the f_h (f_l) mode was 2054.24 (504.91) Hz and 6.6×10^5 (1.3×10^6) at the lowest temperature.

Both the drive and the detection of the oscillation were made with the electrode fins bonded to the torsion head.

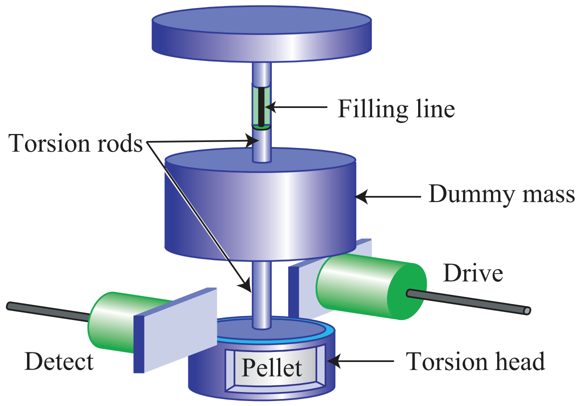

FIG. 1. (Color online) Schematic of a twofold torsional oscillator.

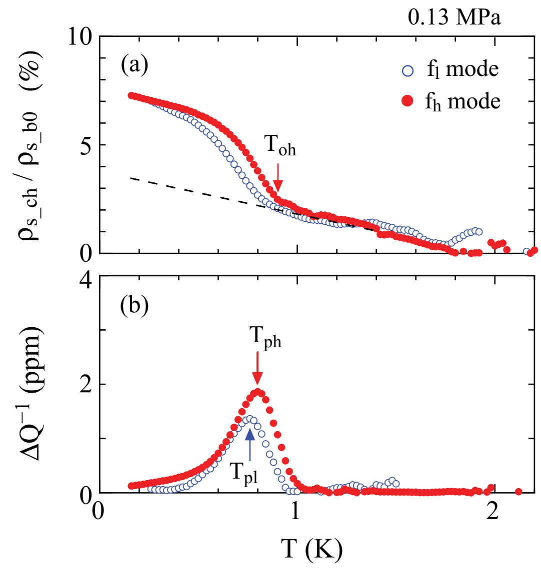

FIG. 2. (Color online) (a) Temperature dependence of the superfluid fraction in the channel divided by the magnitude of background at absolute zero. The dashed line is the extrapolation from the high temperature. (b) Temperature dependence of ΔQ^{-1}. The data for the f_l mode are multiplied by 4.07, the ratio of f_h to f_l.

Most data of the superfluid response were taken under the oscillation amplitude of 0.92 (4.9) μm for the f_h (f_l) mode, corresponding to the rim velocity of 14 (19) mm/s. We also measured the superfluid response for the f_h mode under the rim velocity from 1.4 to 140 mm/s and confirmed that there was no rim velocity dependence.

In order to extract the superfluid response of ^{4}He in the channel, we carried out measurements under the condition when the channel was filled with solid N_2 (the N_2-filled condition) in the same manner as the previous experiments.[14] Under this condition, the increase in resonance frequency came from the superfluid in the open space, whereas, when the channel was filled with ^{4}He (the ^{4}He-filled condition), it came from both the channel and the open space. We separated the net frequency increase due to the superfluid in the channel by subtracting the increase in resonance frequency for the N_2-filled condition from that for the ^{4}He-filled condition. In this paper, the magnitude of the superfluid fraction in the channel ρ_{s_ch} is normalized by the increase for the N_2-filled condition at absolute zero ρ_{s_b0}. The magnitude at the lowest temperature is less than 10% of ρ_{s_b0}, which is about five times smaller than that calculated from the mass of the liquid in the channel and the χ factor of the open space. It may be relevant to the random orientation of the channel. Although the magnitude becomes small because of the orientation, its temperature dependence is not influenced. Regarding the energy dissipation, which is connected to the change in the inverse of the Q factor ΔQ^{-1}, the contribution of the superfluid in the channel corresponds to the difference between N_2- and ^{4}He-filled conditions.

III. RESULTS AND DISCUSSION

Figures 2(a) and 2(b) show the temperature dependence of ρ_{s_ch}/ρ_{s_b0} and ΔQ^{-1} under 0.13 MPa, respectively. The solid (open) symbols represent the data for the f_h (f_l) mode. ΔQ^{-1} for the f_l mode in the figure is multiplied by 4.07, which is the ratio of f_h to f_l. For the f_h mode, the superfluid fraction starts to increase at around 1.8 K and increases gently with decreasing temperature. Then, it shows a rapid growth at the superfluid onset T_{oh} of 0.90 K. Here, we define T_{oh} as the intersection of the extrapolation from high temperatures and the steepest increase. The rapid growth of the superfluid is associated with a large and broad dissipation peak with the maximum at T_{ph} of 0.80 K. With a further decrease in temperature, the increasing rate of the superfluid fraction comes closer to that between 0.9 and 1.8 K. For the f_l mode, the rapid growth of the superfluid fraction shifts to the low-temperature side by 40 mK, whereas, the slow increase below and above this temperature region shows the same behavior as the f_h mode. The dissipation peak temperature for the f_l mode T_{pl} also shifts to the low-temperature side by 40 mK. We found that the superfluid response shifts greatly to the low temperature as the frequency is lowered in the range of torsional oscillator experiments.

The superfluid response is remarkably different from the superfluidity for the three-dimensional (3D) (i.e. bulk) case; it is a typical second-order phase transition where the coherence emerges thermodynamically and shows no frequency dependence. The observed frequency dependence demonstrates that the superfluid phase coherence has a finite relaxation time comparable to the oscillation period, i.e., it is concluded that the rapid growth is a dynamical phenomenon, which is a characteristic feature of the 1D system.

Here, we make a short comment on the two-dimensional (2D) (i.e. film) case. According to the dynamical Kosterlitz-Thouless (KT) theory, the superfluid onset for the film shifts slightly to the high-temperature side with an increase in measuring frequency.[22,23] However, the frequency dependence, estimated from the dynamical KT theory, is 1 order of magnitude smaller than that of the present experiments. This supports the fact that the observed frequency dependence cannot be explained by the dynamical KT theory.

To examine how the dynamical superfluid response varies by the application of pressure, we made measurements under several pressures between 0.13 and 2.4 MPa. The inset of Fig. 3 shows the superfluid response for the f_h mode. As the pressure is increased, the superfluid onset T_{oh} moves to a lower

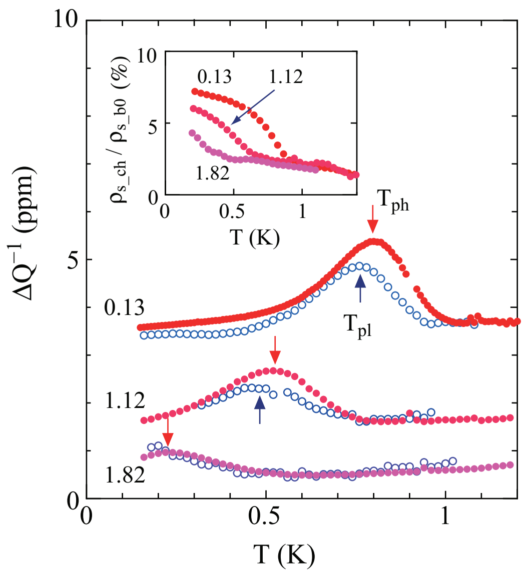

FIG. 3. (Color online) Temperature dependence of ΔQ^{-1} for several pressures. Here, pressures are shown in megapascals. For clarity, the data are shifted vertically. Down and up arrows point to T_{ph} and T_{pl}, respectively. Inset: temperature dependence of the superfluid density for the f_h mode at the corresponding pressures.

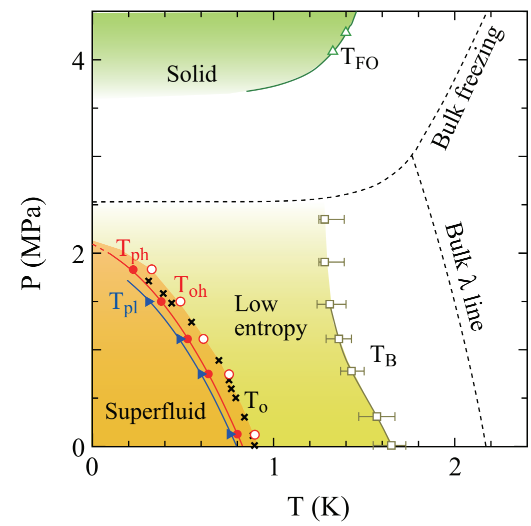

FIG. 4. (Color online) Pressure-temperature phase diagram. T_{ph} (•) and T_{pl} (►) represent the dissipation peak temperatures for the f_h and f_l modes, respectively. T_o for the f_h mode is shown as (○). For comparison, T_o from the previous single torsional oscillator measurements[14] is shown as (×). T_B (the temperature where heat capacity has a bend) and T_{FO} (freezing onset temperature) are also shown as (□) and (△), respectively.

temperature, and the superfluid density decreases, which is the same manner as reported in the previous experiments.[24] Compared with the f_l mode, it was found that the rapid growth for the f_h mode is located at the high-temperature side regardless of pressure. Figure 3 shows the temperature dependence of ΔQ^{-1} for both modes. The dissipation peak temperatures T_{ph} and T_{pl} are suppressed by the application of pressure as the superfluid onset T_{oh} decreases. The difference $T_{ph} - T_{pl}$ increases from 40 mK at 0.13 MPa to 70 mK at 1.50 MPa. T_{pl} was not observed down to the lowest temperature under 1.82 MPa. We found that the frequency dependence of the superfluid response is enhanced by the application of pressure.

The dissipation peak temperature of T_{ph} and T_{pl} and the superfluid onset T_{oh} are plotted in the pressure-temperature phase diagram in Fig. 4, associated with the temperature of a bump in heat capacity T_B at which ^{4}He falls into a low-entropy state. It was found that T_{ph}, T_{pl}, and T_{oh} are located at much lower temperatures than T_B. This means that the dynamical superfluid response occurs in the temperature region where the ^{4}He atoms are in a full low-energy state.

It is natural to consider that the superfluid response of this system is caused by a different mechanism from the 3D and 2D cases because it shows a dynamical behavior in the frequency range of torsional oscillator experiments. We compared the superfluid response of the TL liquid model proposed by Eggel *et al.*[19] with the physical properties of ^{4}He confined in the 2.8-nm channel. In their theory, the superfluid response shows a dynamical behavior and is primarily determined by the Luttinger parameter K. The dissipation peak temperature T_p depends on measuring frequency f as $T_p = Af^{1/(2K-3)}$, where A is a constant.[25] According to this relation, we can obtain K from the ratio of T_{ph} to T_{pl} in the present experiments as $T_{ph}/T_{pl} = (2054\ \text{Hz}/505\ \text{Hz})^{1/(2K-3)}$. As shown in Fig. 4, K decreases with increasing pressure, and the decrease is enhanced at high pressures. This behavior qualitatively explains the observed pressure dependence of T_{ph} (T_{pl}) since T_{ph} (T_{pl}) is suppressed with decreasing K in the theory.

We also evaluate K from the physical properties of ^{4}He in the 2.8-nm channel. K is expressed by these properties as $K = \hbar\kappa\pi v\rho_0^2$, where κ is the 1D compressibility, v is the sound velocity, and ρ_0 is the linear number density, respectively. Here, $v = \sqrt{1/(m\rho_0\kappa)}$, and m is the mass of the ^{4}He atom. We can obtain v from the heat capacity at low temperatures[26] and ρ_0 from the decrease in resonance frequency due to mass loading in the present experiments, e.g., $v = 147$ m/s and $\rho_0 = 2.0 \times 10^{10}$ atoms/m at 0.13 MPa, although ρ_0 includes an ambiguity of 20%. The evaluated value is plotted in Fig. 5.

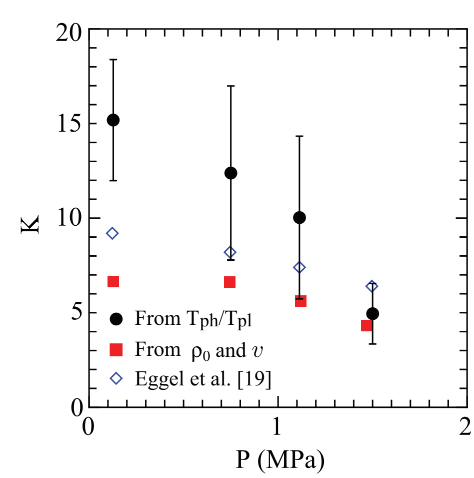

FIG. 5. (Color online) Pressure dependence of the Luttinger parameter K. •: evaluated from T_{ph}/T_{pl} and □: evaluated using ρ_0 and v.[26] ⋄: from the work of Eggel *et al.*[19]

We found that it decreases gradually with increasing pressure. Its pressure dependence agrees with that of K calculated from T_{ph}/T_{pl}, supporting the consistency with the theory. A quantitative discrepancy in these values may come from the ambiguity of adopted quantities in T_{ph}/T_{pl}, ρ_0, and v.

We comment on the difference between the present experiments and that by Vekhov and Hallock.[13] The mass flux in solid ^{4}He was measured under the chemical-potential difference between two reservoirs. It is thought that the flux is carried by small superfluid cores of edge dislocations, which, in the case of screw dislocations, are predicted to have diameters in the range of about 0.6 nm.[12] On the other hand, the superfluid response of liquid ^{4}He in the 2.8-nm channel was measured under the condition that no chemical-potential gradient existed. According to quantum Monte Carlo simulations by Del Maestro *et al.*, the superfluid fraction depends on the channel diameter: For the 2.4-nm channel, the fraction is present at low temperatures, whereas, it is suppressed for the 0.58-nm channel.[18] The large channel may cause the superfluid response of the TL liquid for torsional oscillator measurements. The channel size dependence is left as an experimental future issue.

IV. SUMMARY

We have studied the frequency dependence of the superfluid response for ^{4}He confined in the 2.8-nm channel by twofold torsional oscillator measurements. By a reduction in the measuring frequency from 2000 to 500 Hz, both the superfluid onset and the dissipation peak shift to the low-temperature side by 40 mK under 0.13 MPa, and the shift is slightly enhanced by the application of pressure. It is concluded that the superfluid response of ^{4}He in the channel is a dynamical phenomenon. The observed behavior is consistent with the theoretical prediction based on the TL liquid model.

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