Strong Suppression of the Kosterlitz-Thouless Transition in a ^{4}He Film under High Pressure

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We have found that the surface specularity for ^{3}He quasiparticle scattering is closely related to the superfluidity and the Kosterlitz-Thouless (KT) transition of ^{4}He film adsorbed on the surface. The specularity is determined by measurements of the transverse acoustic impedance of bulk liquid ^{3}He. The unique point of our system is that we can control the correlation among ^{4}He atoms in the film by changing the pressure of the bulk ^{3}He. The observed KT transition temperature is significantly suppressed by increasing the pressure, which suggests a strong correlation effect on KT transition.

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Two-dimensional superfluidity has been well understood by Berezinskii-Kosterlitz-Thouless (abbreviated simply as KT) transition [1]. Similar examples are found in a variety of physical systems such as ^{4}He film [2], superconductor film [3], superconductor in arrays of Josephson junctions [4], Bose-Einstein condensation in atomic gases [5], and so on. Most of them are well explained by KT theory. However, the more correlated regime beyond KT theory is now intriguing, focusing on the physics around the quantum critical point (QCP). Localization and superfluidity are separated by the QCP at $T = 0$ and some scaling behaviors such as $T_c \propto \sigma_s(0)$ are predicted in the vicinity of the QCP. Here, T_c and $\sigma_s(0)$ are the transition temperature and the superfluid density at $T = 0$. In the 2D soft-core generic boson Hubbard model where the strong correlation of the particles is introduced, T_c and $\sigma_s(0)$ are suppressed and go to zero at QCP [6–8]. Such a strong correlation effect should be examined by the experiment.

^{4}He film may be an ideal system with which the strongly correlated bosonic Hubbard model can be tested, if we could enhance the effect of the interparticle repulsive interaction by some compressions and suppress the in-layer motion. This situation can be realized by pressurizing the film with bulk ^{3}He liquid [9,10]. In this Letter, we will report the experimental results on the superfluidity of ^{4}He film under high pressure.

It is known that ^{4}He film changes the surface condition for the scattering of ^{3}He quasiparticles [11,12]. The surface specularity S is a fraction of quasiparticles which scatter specularly. $S = 1$ corresponds to the specular limit and $S = 0$ to the diffusive limit. The bare surface corresponds to $S = 0$, since the atomic scale roughness is relevant [11,12]. S dramatically shifts from 0 to 1 when a few monolayers of ^{4}He film are added. The recent transverse acoustic impedance Z measurement clarified that the energy dispersion of the Andreev bound states exhibits a distinct linear dependence on momentum, forming the so called Majorana cone, in the specular limit [13–15]. It is suggested that the surface condition relates to the superfluidity of ^{4}He film, although it is not understood how the film makes the condition change. Thus, it is important to study what happens in ^{4}He film under bulk ^{3}He.

Z is defined as the ratio of the stress tensor Π_{zx} of the liquid at the surface to the wall velocity u_x as $Z = \Pi_{zx}/u_x$. We used ac-cut quartz transducers, which oscillate transversely, immersed in liquid ^{3}He. The transducers were installed in the cell more than 0.5 mm away from the cell wall. The surfaces of the transducers were plated by gold. More details were described in Refs. [16,17]. The resonance frequency $f(= \omega/2\pi)$ and the Q factor of the transducers were measured by the cw bridge method. Z was obtained as $Z = Z' + iZ'' = (\frac{1}{4} m\pi Z_q \Delta Q^{-1}) + i(\frac{1}{2} m\pi Z_q \Delta f/f)$, where Z_q is the acoustic impedance of the quartz and m is the harmonics number of the transducer [18]. Δf and ΔQ^{-1} are changes from the high temperature limit. The fundamental frequencies of the transducers were 9.56 and 15.5 MHz and higher harmonics $m = 3$, 5, and 7 were also used.

The experimental cell was assembled on a nuclear demagnetization refrigerator. The ^{4}He film was adsorbed on the surface at 10 K and was kept at that temperature overnight in order to make a uniform film. After annealing of the film, the cell was cooled down and then the liquid ^{3}He was introduced to the cell below 0.3 K. The temperature was measured by a ^{3}He melting curve thermometer and a calibrated RuO_2 resistance thermometer. In this Letter, ^{3}He is a normal liquid at all temperatures and pressures. Thicknesses of ^{4}He film n were 2.7 layers (40.1 μmol/m^2), 3.6 layers (51.2 μmol/m^2), and 4.5 layers (63.5 μmol/m^2). The surface area of the inside of the cell including a heat exchanger was 142 m^2, which was large enough to precisely determine n.

S for the ^{3}He quasiparticle scattering was determined by fitting the experimental data using $Z(T, S)$ [19]. $Z(T, S)$ is given as

$$\frac{Z(T,S)}{Z(T,0)} = \frac{1-S}{1-S+SZ(T,0)/L_1(0)}, \quad (1)$$

where $L_1(0) = 15\eta/16\lambda$, and η and λ are the viscosity and the quasiparticle mean free path, respectively. $Z(T, 0)$ was measured at the bare surface.

Figure 1(a) shows temperature dependence of real component Z' of Z at pressure $P = 2.5$ MPa and at $f = 46.6$ MHz. Imaginary component of Z suffered from a large temperature-dependent background. Z' was adopted for the determination of S. Lines are the results of Eq. (1) at various S. In the high temperature region, there was no difference in Z' between coated samples and a bare surface sample, meaning that S was equal to zero in the high temperature region. At a particular temperature T_0, Z' of the coated samples began to deviate from Z' of the bare surface sample. Below T_0, Z' of the coated sample was smaller than Z' of the bare surface sample. Furthermore, temperature dependence of Z' of the coated sample had a maximum which could not be reproduced by Eq. (1) if S was fixed. This behavior indicates that S was dependent on temperature.

We calculated S at each temperature by Eq. (1) and show the temperature dependence of S in Fig. 1(b). As the film thickness decreased, T_0 became lower. S was zero in the high temperature region and began to increase at T_0, indicated by arrows in Fig. 1(b); below T_0, S increased continuously. This behavior means that the surface roughness which causes the diffusive scattering reduced as temperature fell below T_0. However, solid or normal liquid ^{4}He film adsorbed on the surface cannot change the surface roughness on the atomic scale. On the other hand, superfluid would fill up the concavity of the surface, which usually has a large adsorption potential, because superfluid makes the potential uniform and the surface more flat. Therefore, an increase of S indicates an increase of the superfluid density σ_s and it is suggested that the film is superfluid below T_0. At 2.5 MPa and 2.7 layers which was data of the thinnest layers at the highest pressure, $Z'(T)$ had a very small deviation from $Z'(T, 0)$ and it was difficult to derive $S(T)$ and T_0 with good accuracy; they sometimes did not follow the systematic behavior of other data. In the following analysis, we decided to take two limiting cases, including and excluding this data, not to be misguided by that deviated data point.

We therefore assume that superfluid transition occurred at T_0. Because ^{4}He film thickness was on the order of a few monolayers, the transition would be KT transition. T_0 had f dependence at almost all samples, as shown in Fig. 2(a): as f increased, T_0 increased; at larger n, the f dependence became larger. We analyzed the f dependence of T_0 by the dynamic KT theory [20]. In Ref. [21], dissipation peak temperature T_P is given by

$$\frac{T_P - T_{\mathrm{KT}}}{T_{\mathrm{KT}}} = \frac{4\pi^2}{b^2}\left[\frac{1}{2}\ln\frac{14D}{a_0^2\omega}\right]^{-2}. \quad (2)$$

Here, T_{KT} corresponds to the transition temperature at zero frequency, b is a constant, D is the vortex diffusion

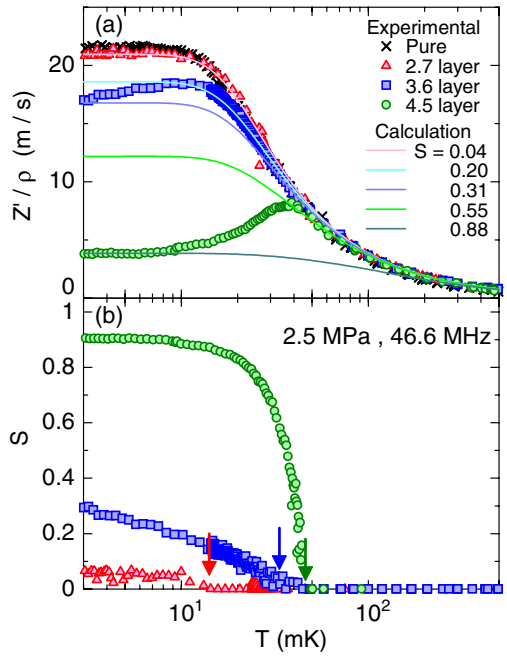

FIG. 1 (color online). Temperature dependence of real component Z' of the transverse acoustic impedance (a) and the surface specularity (b) at various thicknesses of ^{4}He. Pressure is 2.5 MPa and frequency is 46.6 MHz. Lines in (a) are results of calculations [19]. Arrows in (b) indicate T_0 at each thickness.

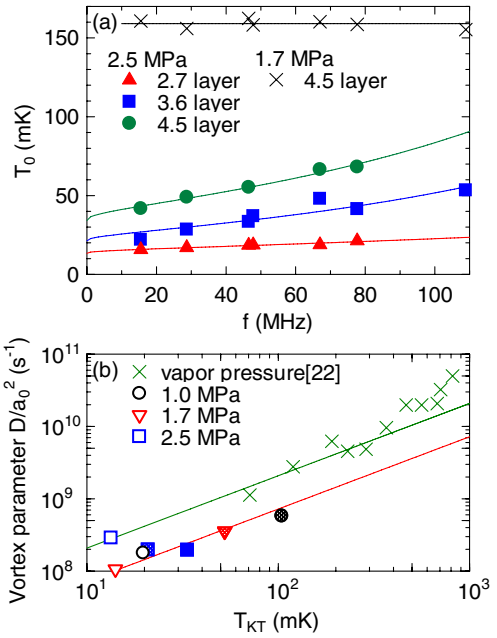

FIG. 2 (color online). (a) Frequency dependence of T_0 at 2.5 MPa. Lines are fittings using Eq. (2) from the dynamic KT model. The intercept of vertical axis in each fitting line corresponds to T_{KT}. (b) T_{KT} dependence of the vortex parameter D/a_0^2. Open, hatched, and closed symbols indicate the data of 2.7, 3.6, and 4.5 layers, respectively. Crosses are at vapor pressure from the pure film experiment [22]. The lines are fittings assuming a linear dependence on T_{KT}.

constant, and a_0 is the vortex core diameter. We assumed that T_P could be approximately T_0. The solid lines in Fig. 2(a) are the fit using Eq. (2) whose fitting parameters are T_{KT} and vortex parameter D/a_0^2. In Fig. 2(b), D/a_0^2 was plotted against T_{KT}. Our results showed that D/a_0^2 was proportional to T_{KT}, which was also observed in the previous film experiment [22]. Because these frequency dependences of T_0 and the temperature dependence of D/a_0^2 were consistent with the dynamic KT theory, we conclude that the specularity change came from the superfluid KT transition of ^{4}He film.

On the other hand, T_0 at 1.7 MPa and the 4.5 layer, which was data of the thickest layers at the lowest pressure, was the highest, 159 mK, and did not show any f dependence, as shown by the crosses in Fig. 2(a). That was explained by the ^{3}He-^{4}He phase separation. From the solubility measurements of ^{4}He in bulk liquid ^{3}He [23], superfluid ^{4}He film phase separated at around T_0 for a sample of corresponding ^{4}He concentration, 0.6%. Under this condition, the KT transition temperature can be higher than the phase separation temperature. Of course, the phase separation also occurred in other samples; however, there the phase separation temperatures were higher than T_{KT}. In that case, because the phase separated ^{4}He film was normal, S did not change at that temperature.

S increased as n increased in the isotherm of S. In a naive assumption, S was expected to be a monotonically increasing function of σ_s. In the static KT theory, σ_s shows the universal jump at T_{KT}, as $\sigma_s(T_{KT})/T_{KT} = 2k_B M^2/\pi\hbar^2$. Here, M is the mass of the ^{4}He atom. On the other hand, in the dynamic KT theory, σ_s increases continuously from T_0. The jump is less clear as D/a_0^2 decreases. In our results, D/a_0^2 decreased as T_{KT} decreased, as shown in Fig. 2(b). Thus, growth of σ_s below T_0 is more gradual as T_0 becomes lower. This gradual growth was also observed in the previous experiments in very thin film [24,25]. The continuous increase of S, shown in Fig. 1(b), can be regarded as a result of the gradual growth of σ_s at high frequencies. Temperature dependence of S, shown in Fig. 1(b), was consistent with the dynamic KT theory without a clear jump at the transition.

To consider the superfluid density at 0 K, we define S at 3 mK as S_0. Figure 3 shows n dependence of S_0. As n decreased, S_0 decreased and seemed to reach zero at a particular thickness n_0. Film thinner than n_0 has been considered to be the inert layer which is strongly adsorbed on the substrate [2,24].

To obtain n_0, we extrapolated S_0 assuming linear n dependence, as shown in Fig. 3. The inset of Fig. 3 is the pressure dependence of n_0. As pressure increased, n_0 increased. This indicates that an increase of the pressure enhanced the localization of ^{4}He adsorbed on the substrate. In the inset, the solid line indicates the pressure dependence of n_0 obtained by the measurement of solubility of ^{4}He in liquid ^{3}He [23]. n_0 at 0 MPa is the only fitting parameter. The good agreement with previous results in the pressure dependence means that the estimation of n_0 was appropriate. Because the inert layer could not move around, effective fluid ^{4}He thickness was $n - n_0$.

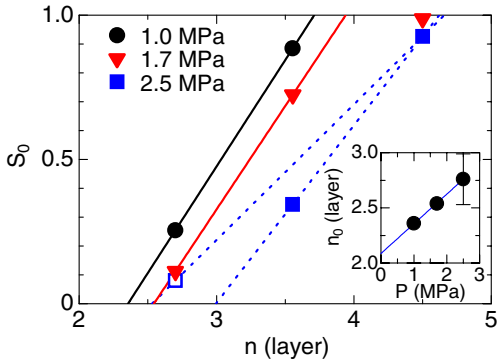

FIG. 3 (color online). Thickness dependence of S at 3 mK at various pressures. Lines are guides for the eye. Because S_0 at 2.5 MPa and the 2.7 layer (the open square) was too small to determine superfluidity clearly, an error of n_0 was estimated by calculations including and excluding that data. Two dotted lines are guides for the eye at 2.5 MPa in the two limiting cases. The inset is the pressure dependence of n_0. The line is obtained by the solubility measurement [23].

T_{KT} is plotted against $n - n_0$ in Fig. 4. In this plot, the effect of the growing inert layers is subtracted. The T_{KT} line for pure films at vapor pressure is also shown as a dashed line in the figure. Our result was more than 15 times lower than the ordinary T_{KT}. As pressure increased, the suppression of T_{KT} became much larger, while $n - n_0$ was not changed so much. Assuming the proportionality between T_{KT} and σ_s, this large suppression of T_{KT} means that only less than 6% of ^{4}He became superfluid at 0 K. On the

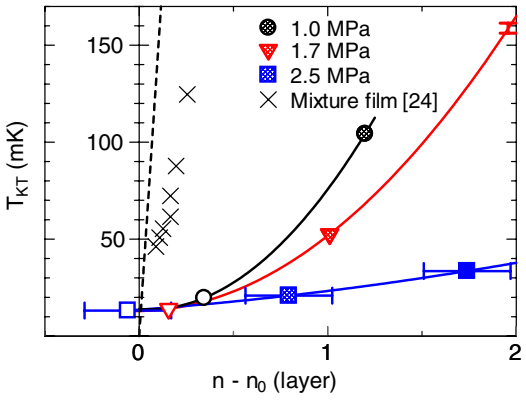

FIG. 4 (color online). Effective thickness $n - n_0$ dependence of T_{KT} at various pressures. Open, hatched, and closed symbols indicate the data of 2.7, 3.6, and 4.5 layers, respectively. Crosses are at vapor pressure from the mixture film experiment [24]. Solid lines are guides to the eye. The dashed line corresponds to T_{KT} for pure films at vapor pressure. The bar at 159 mK is the phase separation temperature T_0 and the actual T_{KT} must be higher.

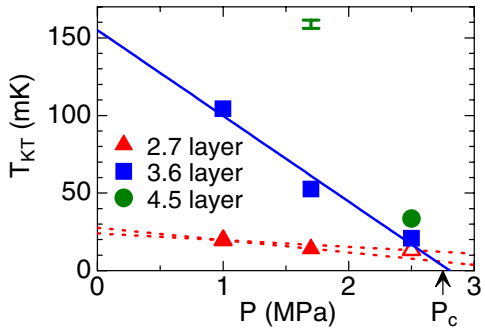

FIG. 5 (color online). Pressure dependence of KT transition temperature T_{KT} at various thicknesses. Observed T_0 at 1.7 MPa and 4.5 layer, indicated as the bar at 159 mK, is the phase separation temperature and thus T_{KT} must be higher. The open triangle is the data at 2.5 MPa and the 2.7 layer and the two dotted lines are guides in the two limiting cases: including and excluding that data.

other hand, in mixture film measurements [24,26], almost all fluid component $n - n_0$ became superfluid at 0 K. Pressurization plays an important role in the suppression of T_{KT} and $\sigma_s(0)$.

The pressure dependence of T_{KT} is shown in Fig. 5. Even at 2.5 MPa, the superfluidity was observed as reported in a previous experiment [27]. A solidification pressure in the films P_s seems to be higher than in the bulk. This is due to the amount of ^{3}He dissolved in the film. As pressure increased, T_{KT} decreased linearly. Especially at the 3.6 layer, T_{KT} extrapolates to zero at 2.75 MPa as indicated by P_c in Fig. 5. This behavior implies that QCP exists at P_c in this system. Under high pressure, the motion of ^{4}He atoms should be suppressed, so, as ^{3}He pressure increases, the strength of hopping t decreases. In the Hubbard model, as t decreases, T_{KT} is suppressed and goes to zero at QCP [6–8]. Our results are consistent with that mechanism where the strong correlation effect is included. Strong suppression of T_{KT} and the proximity to QCP are the first evidence of the strong correlation effect in the 2D boson system where a direct interparticle interaction is the origin of the correlation. Whether P_c is smaller than P_s or not is an intriguing problem which may be related not only to the correlation but also to the disorder of the system. At present, we cannot access this problem because the effect on the impedance should appear only at the lowest temperatures and is very small.

Finally it should be noted that S is increased up to about 0.8 rapidly with the estimated $\sigma_s(0)$ of only 6% of the total fluid density of the film. Though we do not know the microscopic mechanism of the relation between the specularity and the superfluid density, this surprising result would be an important key for the deep understanding of the specularity.

In summary, we observed a superfluid KT transition of ^{4}He films under high pressure liquid ^{3}He by transverse acoustic measurements. Superfluidity was detected as an enhancement of surface specularity S which was calculated from transverse acoustic impedance. Frequency dependence of S was explained by the dynamic KT model. KT transition temperature was significantly suppressed and the existence of QCP was suggested. These behaviors were consistent with the Hubbard model. Our results are evidence that the correlation of atoms in ^{4}He film can be controlled by pressurization.

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