PHYSICAL REVIEW B **74**, 220505(R) (2006)

Spectroscopic study of the surface density of states of superfluid ^{3}He by transverse acoustic impedance measurements

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(Received 15 September 2006; published 6 December 2006; corrected 8 December 2006)

The surface density of states (SDOS) in superfluid ^{3}He at a diffusive wall was investigated by systematic measurements of the transverse acoustic impedance Z. The observed difference between the temperature dependence of Z in the A and B phases can be explained by a difference in the SDOS of each phase. In the B phase, an additional gap in the SDOS opened between the upper energy edge Δ^* of the surface Andreev bound states band and the bulk energy gap Δ. The temperature dependence of Δ^* was measured and was about 30% smaller than the theoretical value. In the A phase, a flat and gapless SDOS was confirmed experimentally.

DOI: 10.1103/PhysRevB.74.220505 PACS number(s): 67.57.Np, 43.58.+z, 74.45.+c

Scattering of quasiparticles by an object modifies the local density of states significantly from the bulk one, leading to the formation of Andreev bound states in unconventional superconductors and superfluids. Since quasiparticles sense the internal phase of the pair potential, the bound states are very sensitive to the symmetry of the order parameters (or the gap structures) and the scattering process. The existence of the bound states at surfaces, impurities, and vortex cores played an essential role in identifying the pairing symmetry of high-transition-temperature superconductors as d wave. Their surface Andreev bound states (SABSs) were observed as a zero-bias conductance peak in the transport measurement of tunneling junctions or scanning tunneling microscopy.[1,2]

Since superfluid ^{3}He is a p-wave superfluid realized in an extremely pure system, its order parameter and various bulk properties are well understood, in contrast to the unconventional superconductors. It provides a good opportunity to study the quasiparticle scattering effect or the Andreev bound states in p-wave BCS states approaching from the well-known bulk superfluids. As shown in Fig. 1, the characteristic subgap structure of the surface density of states (SDOS) in superfluid ^{3}He was calculated theoretically.[3–6] The SDOS is very sensitive to the pairing states of the superfluid and the specularity of the scattering by the surface. However, there had been no proper probe to survey the surface properties for electrically neutral ^{3}He, and not much was known about the surface of superfluid ^{3}He compared with superconductors. Recentry, SABSs were confirmed in superfluid ^{3}He by transverse impedance measurements[7] and surface specific heat measurements near T_c.[8] As for impurity scattering, superfluid ^{3}He in aerogels has been extensively studied in this decade. The density of states is now shown to be gapless in aerogels due to the formation of a broad impurity band of Andreev bound states.[9–12]

Quasiparticles cannot occupy the states within the bulk energy gap Δ in bulk superfluid ^{3}He. However, in the region within several hundred nanometers of a wall (some coherence lengths), the order parameters are suppressed by the wall due to pair breaking, and SABSs are formed there. As shown schematically in Fig. 1, there exist states within Δ in the SDOS. The quasiclassical calculation by Nagato *et al.* predicted a drastic difference in SDOS between the A and B phases shown by the dashed and solid lines in the figure, respectively.[5] In contrast to the gapless and flat SDOS in the A phase, a characteristic bound states band appears at the Fermi level in the B phase and an additional gap opens between Δ and the clear upper energy edge Δ^* of the bound states band. These prominent characteristies of the SDOS in the B phase cause an anomaly at the energy corresponding to an excitation of $\Delta+\Delta^*$ as indicated by the arrow. In our previous work,[7] we demonstrated experimentally and theoretically that measurement of the transverse acoustic impedance Z was a good probe for SABSs. The temperature dependence of Z in the B phase at 17.0 bar had anomalies at a temperature where the acoustic energy was equal to $\Delta+\Delta^*$. In this paper, we studied details of the SDOS by a systematic measurement of Z in the B phase (P=6.0, 10.0, 17.0, 23.0, and 24.9 bars) and the A phase (P=23.0, 24.9, and 27.2 bars) in a frequency range from 9.56 to 109 MHz, and report a temperature dependence of Δ^* in the SDOS.

In order to measure the transverse acoustic impedance ac-cut quartz transducers were immersed in liquid ^{3}He in a sample cell and worked as parallel oscillating boundaries. Information about the momentum transfer from the oscillating wall to ^{3}He quasiparticles can be measured as the change of load. From the Q factor and resonance frequency $f_0=\omega_0/2\pi$ measured by the cw method described in our previous reports,[7,13,14] each component of the complex acoustic impedance $Z=Z'+iZ''$ was obtained as $Z'=\frac{1}{4}n\pi Z_q\Delta(1/Q)$, $Z''=\frac{1}{2}n\pi Z_q\Delta f_0/f_0$, where Z_q is the acoustic impedance of quartz and n is the harmonics number of the transducer.[15]

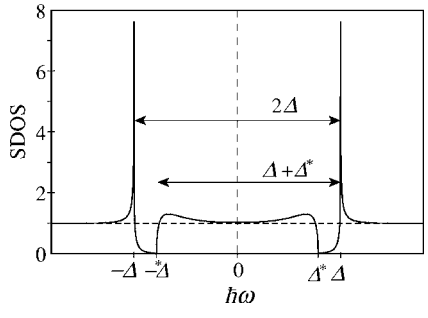

FIG. 1. A schematic view of the surface density of states at a diffusive boundary in the B phase (solid line) and the A phase (dashed line) normalized to the normal state value based on the calculation by Nagato *et al.* (Ref. 5). In the B phase, Andreev bound states lead to a finite density of states below Δ^*.

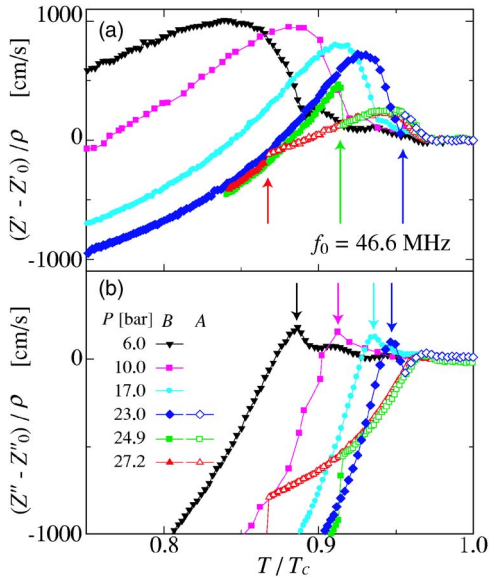

FIG. 2. (Color online) Temperature dependence of real (a) and imaginary (b) components of the transverse acoustic impedance at a frequency of 46.6 MHz and pressures from 6.0 to 27.2 bars as denoted by legends in (b). *A*-*B* transitions are indicated by the upward arrows in (a). In the *B* phase (solid symbols), owing to the pressure dependence of the energy gap, the characteristic shapes of Z are shifted to lower temperatures with lowering pressures. The arrows in (b) indicate the temperatures T^* at which Z'' had peaks. Since there is no Δ^* in the *A* phase (open symbols) the peaks in Z'' disappeared or became very small compared with those in the *B* phase.

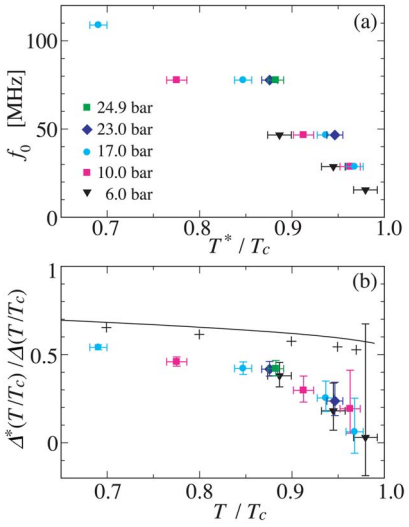

FIG. 3. (Color online) (a) Frequency dependence of T^* in the *B* phase at the pressures denoted therein. (b) Temperature dependence of Δ^* scaled to the bulk gap Δ. Δ^* was deduced by $\Delta^* = \hbar\omega_0 - \Delta(T^*, P)$. The solid line is the plot of the theoretical calculation of Δ^*/Δ. The crosses are also the theoretical calculation determined from the peak positions of Z'' (Ref. 22).

Δf_0 and $\Delta(1/Q)$ represent the changes from an unloaded condition. The transducers were installed in the cell more than 0.5 mm away from the cell wall. Transverse sound was damped in the bulk. Although propagation of transverse sound in superfluid ^{3}He was detected as a standing wave inside a cavity of some tens of micrometers,[16–18] the reflected wave, which traveled in the bulk and contained the bulk information, never influenced the response of the transducers in our experimental configuration. Thus, only the coupling between the transducer's wall and liquid ^{3}He determines the detected change of the impedance. Using two ac-cut quartz transducers with fundamental frequencies of 9.56 and 15.5 MHz, we carried out the spectroscopic measurement at the frequencies of 9.56, 15.5, 28.7, 46.6, 77.7, and 109 MHz. The liquid ^{3}He inside the experimental cell was cooled by a nuclear demagnetization refrigerator through a sintered silver heat exchanger. The temperature was measured by a ^{3}He melting curve thermometer mounted on the nuclear stage. The temperature of liquid ^{3}He was calibrated against the pair-breaking temperatures at 9.56 MHz at several pressures.

The pressure dependences of Z' and Z'' at $f=46.6$ MHz in the warming process are plotted in Fig. 2 as denoted by legends therein. Changes from the normal state value Z'_0 and Z''_0 below T_c are shown. Jumps appeared in both Z' and Z'' simultaneously at temperatures indicated by upward arrows in Fig. 2(a) and also at all other frequencies. These jumps showed supercooling behavior[19] and their temperatures agreed with the known *A*-*B* phase transition temperature[20] within experimental accuracy in the warming process. Jumps in transverse acoustic response have been used to map the *A*-*B* transitions,[21] although it is not trivial how Z responds to the *A*-*B* transition. Our measurements can provide exact values of the discontinuous changes in Z' and Z'' separately at the *A*-*B* phase transition. Z in the *A* phase is shown by open symbols and in the *B* phase by solid symbols in Fig. 2.

The characteristics of the observed temperature dependence at various frequencies at a fixed pressure of 17.0 bar in Ref. 7 are reproduced by the results in the *B* phase of Fig. 2; Z' began to increase at the pair-breaking temperature T_{pb} with cooling, Z' had a kink and Z'' had a peak at T^* as indicated by the downward arrows in Fig. 2(b), and Z' had a broad peak at lower temperatures. We concluded in Ref. 7 that T^* was the temperature at which $\hbar\omega_0 = \Delta(T^*, P) + \Delta^*$ and Z' and Z'' had anomalies. With lowering pressure, the characteristic shapes of the temperature dependence were shifted to lower temperature due to the pressure dependence of Δ. Thus, lowering the pressure is found to be equivalent to increasing the frequency. These pressure dependences were also measured at other frequencies.

We measured T^* at various pressures and frequencies from the peaks in Z'', which were able to be determined more accurately than the kinks in Z'. The results of T^* are shown in Fig. 3(a). At low frequencies the peaks were sometimes not clear and not included in this plot. T^* was lower at higher frequencies and at lower pressures. Since $\hbar\omega_0$ corresponds to the excitation $\Delta(T^*, P) + \Delta^*$ at T^*, we can deduce $\Delta^*(T, P)$ as $\Delta^* = \hbar\omega_0 - \Delta$. We calculated the bulk energy gap $\Delta(T^*, P)$ from the phenomenological weak coupling plus energy gap given in Ref. 15. The results of Δ^* scaled to Δ are plotted against the reduced temperature T/T_c in Fig. 3(b) with the error bars coming from the uncertainty of the absolute temperature ± 20 μK in these measurements. The solid line and

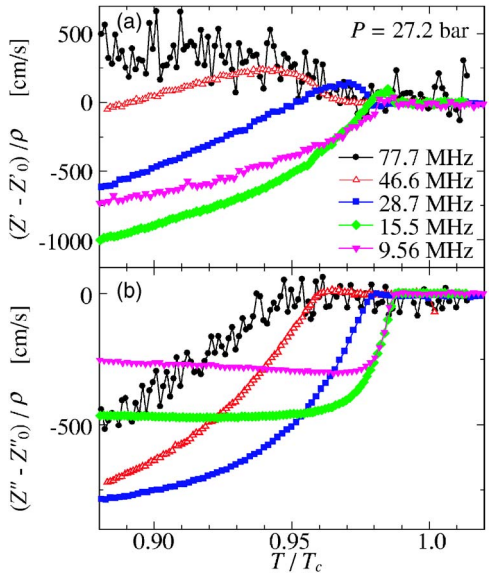

FIG. 4. (Color online) Temperature dependence of real (a) and imaginary (b) components of acoustic impedance in the A phase taken in the warming process at 27.2 bar at various frequencies.

crosses are the plots of the theoretical calculations;[22] the solid line is Δ^*/Δ, and the crosses are determined from the peak positions of $Z''(T)$. They come close to each other as expected. We have a large scatter in data near T_c due to the steep change of $\Delta(T)$. The observed Δ^*/Δ is about 30% smaller than the theoretical values at low temperatures but has a similar temperature dependence.

There are significant differences between the temperature dependence of Z in the A and B phases. The peaks in Z'' in Fig. 2 in the B phase were not observed in the A phase. Since the peaks represent the excitation of $\Delta+\Delta^*$ as mentioned above, this result is clear evidence that the observed acoustic impedances for both phases were correctly reflected by the subgap structure in the Balian and Werthamer (BW) state and the flat SDOS in the Anderson, Brinkman, and Morel (ABM) state, respectively. Figure 4 shows the result at $P=27.2$ bar where the A phase can exist in bulk superfluid ^{3}He in a wider temperature range. Z' and Z'' at 9.56–77.7 MHz are shown by symbols explained therein. The quasiclassical theory in the ABM state with a diffusive boundary[23] reproduces the characteristics of the measured temperature and frequency dependence of Z' and Z'' in the A phase; with increasing frequency, the temperature where a peak appears in Z' decreases, the initial slope of Z'' decreases at T_c, and the magnitude of Z'' in the low-temperature limit decreases. Thus, the validity of transverse acoustic impedance measurements to investigate the surface properties of superfluid ^{3}He was also confirmed by the results in the A phase. However, we have one discrepancy between the experiment and the theory. The temperatures at which Z'' started to decrease became lower with increasing frequency while the theory predicted that Z'' should start to decrease at T_c regardless of frequency.[23] Improvement of the theory in the ABM state is surely needed.

The subgap structure of the SDOS in the BW state was calculated theoretically by several groups.[3–6] At a specular surface, the bound-state energy ε is approximately determined by $\varepsilon=\pm\Delta\sin\theta$, where θ is the incident angle measured from the normal to the surface. In the case of normal incidence $\theta=0°$, a δ-function-like bound state is formed at the Fermi energy (i.e., $\varepsilon=0$). In the grazing incidence limit $\theta\sim 90°$, a bound state is formed near Δ. Therefore, by averaging over all possible angles, the bound states between the two limits fill the energy gap and the SDOS becomes gapless at the specular surface. At a diffusive surface ε is broadened and shifted to lower energy. Zhang argued that the formation of Δ^* is due to the suppression of the parallel component of the order parameter $\Delta_\parallel$ at the diffusive surface;[4] $\Delta_\parallel<\Delta$, and thus bound states cannot fill the states between $\Delta_\parallel$ and Δ. However, it was reported that Δ^* exists in the BW state at a diffusive surface even with a spatially uniform order parameter assumed.[5,24] Although the uniform-order-parameter assumption is rather fictitious, Δ^* is presumably formed not only by the suppression of the order parameter but also by the diffusive scattering itself. The origin of Δ^* has not been fully clarified yet and our measurement will be important information.

The measured Δ^* was significantly smaller than the theoretical value. So far calculations of both the SDOS and Z have been made only in the weak-coupling limit without Fermi liquid corrections. It is intriguing to see how the strong-coupling effect modifies SDOS and Z. The theory[4–6] showed that the SDOS strongly depended on surface specularity. Since all measurements were carried out on the same diffusive surface, it will be useful to alter the quasiparticle reflection properties by coating the wall with thin layers of ^{4}He or hydrogen in order to have further insight into the surface properties of the ^{3}He B phase experimentally.

In conclusion, we investigated the surface properties of superfluid ^{3}He by systematic measurements of transverse acoustic impedance in the A and B phases. The temperature dependence of Z' and Z'' was dominated by a coupling between a transversely oscillating wall and ^{3}He quasiparticles in SABSs. The observation of the A-B phase transition as a large jump of Z demonstrated that the transverse acoustic response was sensitive to the change in the symmetry of the order parameter through the change of the SDOS. Using this powerful probe, the subgap structures at the surface of the p-wave superfluid were found. While in the A phase the SDOS is gapless and flat, in the B phase it has a clear upper energy edge Δ^* of the SABS band. Δ^* is smaller than the theoretical expectation but has a similar temperature dependence.

We would like to thank Y. Nagato, M. Yamamoto, S. Higashitani, and K. Nagai for providing us with their calculations before publication. We are grateful to W. P. Halperin, J. A. Sauls, and Y. Lee for stimulating discussions. M.S. acknowledges support from JSPS. This work was partly supported by the Kurata Memorial Hitachi Science and Technology Foundation, a Grant-in-Aid for Scientific Research, and the 21st Century COE Program at Tokyo Tech "Nanometer-Scale Quantum Physics" by the Ministry of Education, Culture, Sports, Science and Technology, of Japan.

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