New Anomaly in the Transverse Acoustic Impedance of Superfluid ^{3}He-B with a Wall Coated by Several Layers of ^{4}He

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We measured the transverse acoustic impedance of superfluid ^{3}He-B with a wall coated by several layers of ^{4}He. The coating is known to enhance the specularity in quasiparticle scattering by the wall. We found a new anomaly, a bump and a peak, in the temperature dependence of the transverse acoustic impedance. This agrees with a theoretical calculation using a partially specular wall boundary condition. The new anomaly is shown to arise from a change in the surface density of states by coating and the scattering of thermally occupied surface bound states to other states. The change is towards the density of states of Majorana cone in the specular limit.

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A universal feature of unconventional superconductors and superfluids is the existence of low-energy midgap states in the vicinity of the surface and/or interface [1–5], which are called Andreev–Saint-James surface bound states (ASJ-SBS). ASJ-SBS govern the transport properties of superconductors and superfluids, since the system always communicates with its environment through the surface. For example, the zero-bias conductance peak (ZBCP) in the tunneling spectrum of high T_c superconductors [4,5] has been ascribed to the zero-energy bound states. ZBCPs were also observed in other superconductors, such as Sr_2RuO_4 [6], κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Br [7], UBe_{13} [8], and $CeCoIn_5$ [9], and this was regarded as evidence of their unconventionality. The ASJ-SBS in p-wave pairing superfluid ^{3}He was not observed until recently, because of the lack of an appropriate probe for the neutral superfluid. Aoki *et al.* [10] showed that the transverse acoustic impedance Z provides information on the density of states of the bound states in superfluid ^{3}He-B.

ASJ-SBS occur in general when the order parameter has antisymmetry under the reflection by the surface. However, they do not necessarily appear as the zero-energy peak in the surface density of states (SDOS) when the simple antisymmetry is not satisfied. Examples of such states are the $d + is$ state and the Balian-Werthamer (BW) state [4]. In the presence of a subdominant interaction as an s-wave in high T_c superconductors, the $d + is$ can be stabilized near the surface [11] and was proposed as a candidate to explain the splitting of ZBCP observed in tunneling experiments [12,13]. Although the $d + is$ pairing state is a very interesting surface state which breaks time-reversal symmetry, experimental results are still controversial due to the sensitivity of ASJ-SBS to surface condition [12,14–17]. In the BW state, realized in superfluid ^{3}He-B, the simple antisymmetry is also violated because of the existence of an order parameter component parallel to the surface. The BW state has an isotropic energy gap in bulk and anisotropy is introduced by the surface. The bound state energy is zero for the Fermi momentum normal to the surface, but disperses towards the bulk energy gap as the direction of the Fermi momentum approaches the grazing angle, thereby forming an ASJ-SBS band. The ASJ-SBS in this system have recently attracted much attention as Majorana fermion surface states which characterize the topological nature of the bulk BW state [18–22]. Since superfluid ^{3}He is a clean system and the symmetry of its bulk pairing states is well established, it is a suitable system to study complicated behavior of the ASJ-SBS without suffering from ambiguities in pairing states, impurity effects, and so on. Moreover, the surface condition can be varied by coating the surface with several layers of ^{4}He [23–25]. We have found a new anomaly, a bump and a peak, in the transverse acoustic impedance $Z(T)$ of superfluid ^{3}He-B with a wall coated by ^{4}He. We show that the change in SDOS by ^{4}He coating and the thermal occupation of the ASJ-SBS are the origin of the anomaly in the temperature dependence of the impedance.

Calculations of SDOS in superfluid ^{3}He-B have been reported for various boundary conditions, as shown in Fig. 1 [26–29]. In the random S-matrix model [27,30], the roughness of the wall can be described by the specularity factor S in the normal state; the fraction S of quasiparticles is scattered specularly off the wall, while the remaining $1 - S$ is scattered diffusively. In the specular limit $S = 1$, SDOS has a linear dependence on energy near zero energy and a large peak appears at a higher energy than the bulk energy gap Δ because of the enhancement of the parallel component of the order parameter [27,28]. The linear dependence comes from the dispersion relation of ASJ-SBS which is recently called the Majorana cone [18–22]. At finite specularity $S > 0$, there appears a subgap below Δ accompanied by a sharp edge of the bound states

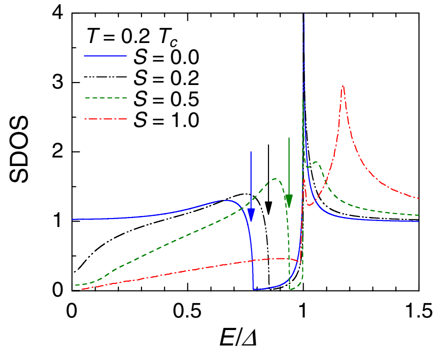

FIG. 1 (color online). Surface density of states of the BW state as a function of energy for typical surface conditions [29]. The arrows indicate the band edge energy Δ^*/Δ.

band. The higher energy peak found in the specular limit is now suppressed in accordance with the suppression of the parallel component of the order parameter, while a characteristic peak appears just below the band edge. In the diffusive scattering limit $S = 0$, the peak in SDOS is minimal and a nearly-flat band is formed. We define the band edge energy as Δ^*, indicated by the arrows in Fig. 1. Δ^* shifts to lower energy as the specularity is reduced. It was shown that $Z(T)$ without a ^{4}He coating has a singularity at a temperature T^*, where the measured angular frequency $\hbar\omega$ corresponds to $\Delta + \Delta^*$ [10,31].

The complex transverse acoustic impedance Z was measured using an AC-cut quartz transducer, immersed in superfluid ^{3}He and oscillating transversely. Z is defined as the ratio of the stress tensor Π of the liquid at the surface to the wall velocity u as $Z = \Pi/u$. We measured the resonance frequency $f(= \omega/2\pi)$ and the Q factor of the transducers by the cw bridge method [10,31]. Z was obtained as $Z = Z' + iZ'' = (\frac{1}{4} n\pi Z_q \Delta Q^{-1}) + i(\frac{1}{2} n\pi Z_q \Delta f/f)$, where Z_q is the acoustic impedance of quartz and n is the harmonics number of the transducer [32]. The liquid ^{3}He 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 and by a vibrating wire thermometer immersed in the liquid ^{3}He.

Coating a wall with thin layers of ^{4}He alters S, and S depends on ^{4}He thickness and the bulk pressure of ^{3}He [23–25]. We make use of the *in situ* controllability of S. The thickness of the ^{4}He coverage we introduced was 2.7 layers (40.1 μmol/m^2) and 3.6 layers (51.2 μmol/m^2). In each case, S was estimated experimentally by measurement of $Z(T)$ in normal liquid ^{3}He as reported in Ref. [33].

Figure 2 shows the temperature dependence of Z' and Z'' at pressure $P = 1.7$ MPa and $f = 28.7$, 47.8, and 67.0 MHz. Here, changes from the normal liquid value Z_0 just above T_c are plotted and ρ is the density of ^{3}He. In the pure sample, which corresponds to the diffusive limit $S = 0$, Z' and Z'' decreased smoothly well below T^* indicated by the vertical lines shown in the insets of Fig. 2.

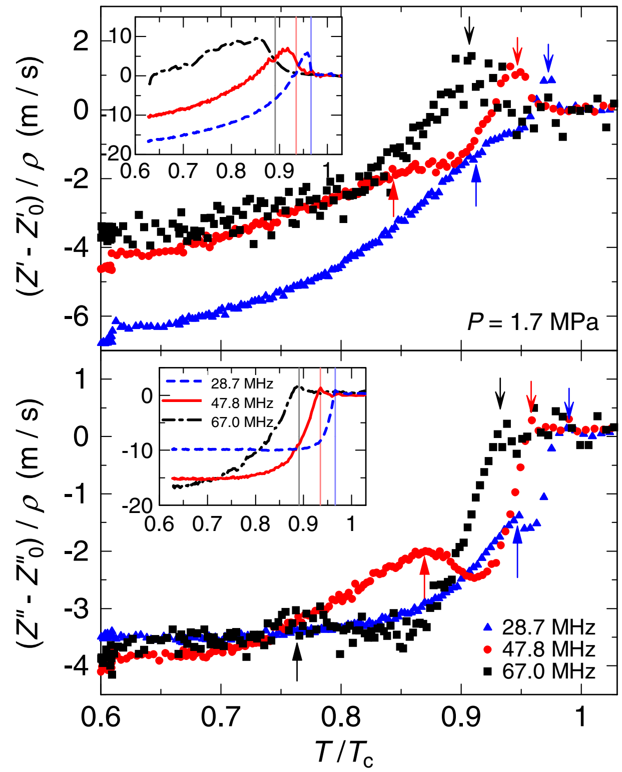

FIG. 2 (color online). Temperature dependence of real Z' and imaginary Z'' components of the transverse acoustic impedance. The surface was coated with 3.6 layers ^{4}He and $S = 0.53$. The insets are the results of pure sample at $S = 0$. (See text.)

On the other hand, a new low-temperature anomaly, a bump in Z' and a peak in Z'' indicated by upward arrows, appeared well below T^* for the coated sample with $S = 0.53$. The downward arrows indicate the high-temperature peaks around T^*. These structures were clearly observed in samples whose S was larger than 0.5, although they did exist in smaller S samples. The anomaly also exists at $P = 1.0$ and 2.5 MPa, where we carried out the measurement in superfluid B phase including the data presented in Ref. [33].

Figure 3 shows Z' and Z'' for $S = 0$, 0.06, and 0.53 as a function of the normalized energy $\hbar\omega/\Delta(T)$ at $P = 1.7$ MPa. $\Delta(T)$ was calculated using the weak-coupling plus model [32]. Vertical axes were normalized to $(1 - S)Z'_{0,\mathrm{pure}}$ in order to see the data at various S on the same scale. Here, $Z'_{0,\mathrm{pure}}$ is the normal state value of Z' just above T_c without coating. The magnitude of the temperature dependence of Z was reduced by a factor of roughly $1 - S$ in the coated sample, since only the diffusively scattered fraction $1 - S$ contributed to Z, while the specularly scattered fraction S did not contribute.

The high-energy peak at $S = 0.53$ appears at a higher energy than at $S = 0$, as indicated by downward arrows in Fig. 3. This is due to the broadening of the bound states band on a partially specular wall as previously reported in

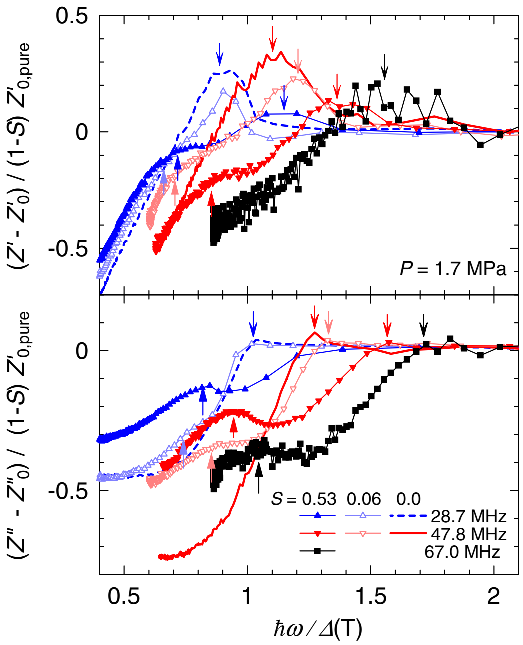

FIG. 3 (color online). Energy dependence of real Z' and imaginary Z'' components of the transverse acoustic impedance. The acoustic energy $\hbar\omega$ was normalized to the superfluid gap energy $\Delta(T)$. The vertical axis was normalized to $(1-S)Z'_{0,\mathrm{pure}}$. The solid and open symbols are the cases of coated samples with 3.6 ($S = 0.53$) and 2.7 layers ($S = 0.06$) of ^{4}He, respectively. Thick lines represent the pure sample case at $S = 0$. (See text.)

Ref. [33], in agreement with theoretical predictions [29,34]. A low-energy anomaly, the bump in Z' and the peak in Z'' indicated by upward arrows, which corresponds to the low-temperature anomaly in $Z(T)$, is clearly visible. As mentioned above, the anomaly exists even in the sample with a small specularity of $S = 0.06$. In the pure sample with $S = 0$, however, Z has only the high-energy peak and decreases smoothly at lower energy.

The new anomaly can be reproduced theoretically using the random S-matrix model [29,34]. Since details of the calculations have already been published, only the results are shown here. Figures 4(a) and 4(b) show the temperature dependence of Z' and Z'' at $f = 46$ MHz and $P = 1.7$ MPa. Z' and Z'' at $S = 0$ (dotted lines) have a single high-temperature peak (downward arrows) and decrease monotonically at lower temperatures in the experimental temperature range. Z' and Z'' at $S = 0.5$ (solid lines) have another peak at lower temperature (upward arrows). The peak in Z' is less pronounced than that in Z'', and may have appeared as the bump experimentally. In Fig. 2, the anomaly is most pronounced at 47.8 MHz and is not clearly seen at 67.0 MHz. This tendency is also found in the theoretical results shown in Figs. 4(c) and 4(d).

Similar behaviors are also found in the frequency dependence of Z at a fixed temperature $T = 0.9T_c$, as shown by the solid lines in Figs. 5(a)–5(d). Two peaks appear at $S = 0.5$ [Figs. 5(a) and 5(b)] and only a high-energy peak

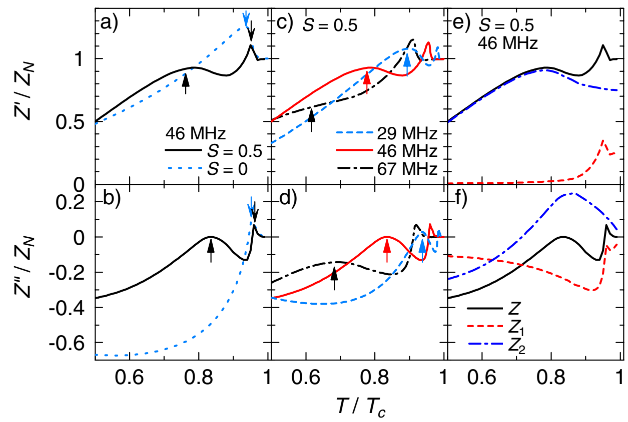

FIG. 4 (color online). Theoretical calculation of the temperature dependence of Z' and Z'' normalized to the normal state value Z_N. The solid and dotted lines are the total value of Z at $S = 0.5$ and 0 in (a) and (b). The total value of Z at the experimental frequencies in (c) and (d). The dashed and dot-dashed lines are the contribution from the pair excitation (Z_1) and the scattering of thermally occupied bound state quasiparticles (Z_2) in (e) and (f).

appears at $S = 0$ [Figs. 5(c) and 5(d)]. The low-energy (high-energy) peaks are indicated by upward (downward) arrows. The characteristics observed in Fig. 3 are well reproduced theoretically.

To explore the origin of the new anomaly in $Z(T)$ at $S > 0$, we separate the impedance Z into two contributions, $Z = Z_1 + Z_2$, where Z_1 is from the pair excitation and Z_2 is from the scattering of thermally occupied quasiparticles [34]. The separation can be performed in a similar manner to BCS theory treatment of sound absorption in superconductors. The dashed and dot-dashed lines in Figs. 4(e)

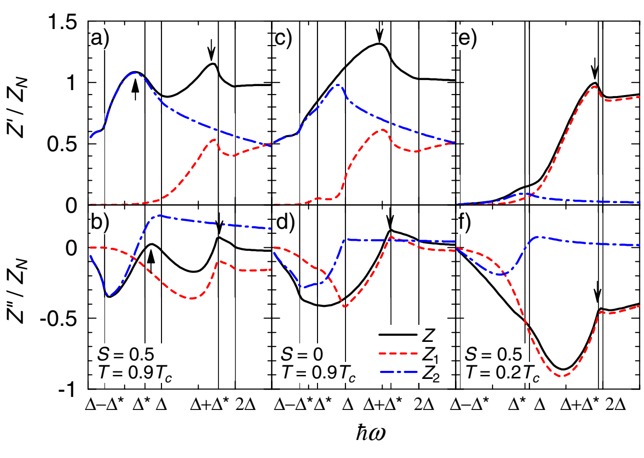

FIG. 5 (color online). Theoretical calculation of the frequency dependence of Z' and Z'' normalized to the normal state value Z_N at $S = 0.5$ and 0. The solid lines represent the total value. The dashed and dot-dashed lines are the contributions from the pair excitation (Z_1) and the scattering of thermally occupied bound state quasiparticles (Z_2), respectively. Temperatures are specified in each figure.

and 4(f) are Z_1 and Z_2, respectively. It is obvious that the low-temperature peaks are caused by Z_2, while Z_1 gives rise to the high-temperature peaks.

We also present the frequency dependence of Z_1 and Z_2 by the dashed and dot-dashed lines in Fig. 5, respectively. We can see at $S = 0.5$ that the low-energy peaks are caused by Z_2 and the high-energy peaks by Z_1. The sharp increase in Z_2' at $\hbar\omega = \Delta - \Delta^*$ in Fig. 5(a) indicates the onset of the scattering of thermally occupied surface bound states to the propagating quasiparticle states. The rapid decrease of Z_2' at higher frequencies reflects the peak structure of the bound states density of states on the finite specularity wall (see Fig. 1) and is the origin of the double-peak structure of Z'. In the diffusive limit $S = 0$, on the other hand, the bound states band is nearly flat below Δ^*, and more featureless than at $S > 0$ as shown in Fig. 1. The low-energy peak becomes obscured and only the high-energy peak is distinct around $\hbar\omega = \Delta + \Delta^*$, as shown in Fig. 5(c). The importance of the thermal excitations at higher temperatures can be seen by comparison with the frequency dependence of Z at $T = 0.2T_c$ in Figs. 5(e) and 5(f). Only the high-energy peaks appear at $T = 0.2T_c$ because of the negligibly small number of thermally occupied quasiparticles. It can be concluded that the scattering process of the thermally occupied bound state quasiparticles is the origin of the new experimentally observed anomaly.

In Fig. 2, the low-temperature anomaly is not so clearly observed at 67.0 MHz. This is because the number of thermal quasiparticles becomes smaller in the low-temperature range where the anomaly should appear at that frequency. The theory well reproduces the experiment but gives a little larger peak in Z''. Better agreement will be obtained by taking into account the Fermi liquid effects as well as the strong coupling correction, which were not considered in the theory.

In conclusion, a new anomaly was observed in the temperature dependence of transverse acoustic impedance in the ^{3}He-B phase when the surface was coated by ^{4}He film. The anomaly arises from the change in SDOS on a wall of finite specularity. The bound states density of states is suppressed at low energies and form a peak structure. This change is in a direction to the SDOS of Majorana cone which appears in the specular limit. By comparison with the theoretical calculation of the impedance, the scattering process of thermally occupied bound state quasiparticles was concluded to be the origin of the anomaly. Combined with our previous report on the broadening of the bound state band on a specular wall [33], the characteristic change of SDOS by the boundary condition has been revealed. Well-established pairing states and the controllability of the boundary condition in superfluid ^{3}He allowed this systematic study of the Andreev Saint-James surface bound states in unconventional BCS states.

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