Vortex Emission by a Low-frequency Vibrating Wire in Superfluid $^3$He-B

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Abstract. We report the investigation of vortex emission by a vibrating wire in superfluid $^3$He-B at a pressure of 28 bar. We used two vibrating wires with 47 Hz and 183 Hz resonance frequencies as a generator and a detector of vortices. The onset velocity of vortex emission for the 183 Hz vibrating wire is higher than a pair-breaking velocity, indicating that pair breaking causes vortex generation. In contrast, the onset velocity for the 47 Hz vibrating wire is lower than the pair-breaking velocity. This result suggests that another mechanism of vortex emission arises for the lower-frequency vibrating wire: pair breaking due to local flow enhanced by protuberances on the surface of the wire, or instability of remanent vortices attached to the wire by vibration.

1. Introduction
Quantum turbulence has been studied using an oscillating object in both superfluid $^4$He [1, 2, 3] and $^3$He-B [4, 5]. In previous works [6, 7], we reported the transition to turbulence due to instability of remanent vortices in superfluid $^4$He. Vortices nucleate during the superfluid transition and remain firmly attached to boundaries. Remanent vortices forming bridges between an object and a surrounding wall can emit vortex rings at oscillating velocities exceeding a critical velocity. The turbulent transition due to bridged vortex lines is also supported by numerical simulations [8].

In contrast with superfluid $^4$He, turbulence in superfluid $^3$He-B is caused by pair breaking [4]; i.e. the onset velocity of turbulence is higher than a pair-breaking velocity. Pair breaking generates normal fluid component in superfluid, likely to nucleate vortex seeds. Vortex seeds around an oscillating object can grow up to a vortex tangle by oscillation, forming turbulence. However, turbulence due to remanent vortices using an oscillating object has not been observed in superfluid $^3$He-B yet. Remanent vortices are considered to remain in superfluid $^3$He, attached to heterogeneous boundaries [9]. Therefore, instability of remanent vortices by oscillation is expected to cause turbulence if they are attached to an oscillator, as observed in superfluid $^4$He [6]. In superfluid $^3$He-B, pair breaking causes turbulence; therefore, the onset velocity of turbulence due to remanent vortices is needed to be lower than a pair breaking velocity for observing this turbulence. Our recent work in superfluid $^4$He revealed that the critical velocity of turbulent transition due to remanent vortices decreases with decreasing oscillation frequency. A low-frequency wire is expected to realize the detection of the turbulent transition due to remanent vortices in superfluid $^3$He-B. Pair-breaking velocity $v_p$ can also be controlled by pressure of $^3$He, because it is attributed to Landau critical velocity $v_L$. At the zero temperature limit, $v_L \sim \Delta(0)/p_F$ in superfluid $^3$He-B, where $\Delta(0)$ is the B-phase energy gap and $p_F$ is the Fermi momentum. A previous study [4] reported that the value of $v_p$ is estimated to be $v_L/3$ at 0 and 5 bars. Therefore pair-breaking velocity $v_p$ increases
with increasing pressure. In this paper, we report the investigation of the onset of vortex emission by a low-frequency vibrating wire in superfluid $^3\text{He}$-B at a pressure of 28 bar.

2. Experimental

We used two vibrating wires, made of NbTi superconducting wire with a diameter of 3 $\mu$m. The wires were formed in semicircles with two legs fixed to pillars, as shown in Fig. 1. The distance between the legs of a wire was 10 mm and 4 mm. They were mounted on a plate made of stycast 1266, in parallel with each other with a space of 3.2 mm between them. Their heights were adjusted to each other. We covered the wires with a silver box.

We placed the wires in a cell used in a previous work [10]. The wires and the silver box were located at the top of the cell and a heat exchanger made of sintered silver was located at the bottom of the cell for thermal contact. Temperature was measured by a Pt-NMR thermometer located near the wires in the cell so as to obtain the temperature of a bulk liquid directly. The cell was mounted on a copper nuclear stage, which was capable of cooling $^3\text{He}$ down to 0.4 mK.

The wires were applied a magnetic field of 27.4 mT, driven by ac electric currents. We measured the amplitudes and the resonance frequencies of the wires simultaneously using a phase locked loop technique as used in a previous work [6]. We measured the resonance frequencies of the vibrating wires in vacuum: 47 Hz for the 10 mm vibrating wire and 183 Hz for the 4 mm vibrating wire. We filled $^3\text{He}$ liquid in the cell through a filling line. We performed simultaneous experiments using the two wires: a generator and a detector of vortices. During keeping the detector vibration at a low drive force, we took simultaneously the responses of the generator and the detector with increasing drive force of the generator. We performed measurements in superfluid $^3\text{He}$-B at a pressure of 28 bar.

3. Results and discussion

Figure 2(a) shows the peak velocities of the 183 Hz vibrating wire as a function of drive force at 0.17$T_c$, where $T_c$ is the superfluid transition temperature. At low drive forces, the velocity increases with increasing drive force deviated upwards from a linear dependence. This upwards dependence is caused by the excitation spectrum due to superflow and Andreev reflection [11]. At high drive forces, the velocity saturates from the dependence observed at low drive forces, suggesting that pair breaking causes energy dissipation in the wire vibration. Consequently, the pair-breaking velocity $v_p$ is estimated to be 19 mm/s, and therefore $v_p = 0.3v_{L}$. This is consistent with a previous study at low pressures [4].
Figure 2. Velocity of the generator 183 Hz wire (a) and the detector 47 Hz wire (b) in $^3$He-B at 28 bar as a function of drive force of the generator. The broken line shows the onset of vortex emission (see text).

Figure 3. Velocity of the generator 47 Hz wire (a) and the detector 183 Hz wire (b) as a function of drive force of the generator. Data shown in Fig. (a) scatter at drive forces above the onset of vortex emission (see text).

We also measured the velocity of the 47 Hz vibrating wire as a detector of thermal excitations. As the drive force of the 183 Hz vibrating wire (generator) is increased, the velocity of the detector decreases because of increase of thermal excitations due to generator oscillation. However, the velocity of the detector increases in a range from 0.09 nN to 0.12 nN, as shown in Fig. 2(b). In this range, the velocity of the generator increases monotonously, and therefore the thermal excitations also increase. These results indicate that the detector is screened from thermal excitations. A previous study [4] reported that vortices emitted from a generator vibrating wire can screen a detector vibrating wire from thermal excitations, resulting in the increase of detector velocity. We therefore conclude that vortices are emitted from the generator at drive force of 0.09 nN. The onset velocity $v_c$ of vortex emission for the 183 Hz vibrating wire is estimated to be 21 mm/s, which is higher than the pair-breaking velocity 19 mm/s. This result is consistent with that in a previous study [4], indicating that vortex nucleation is caused by pair breaking for the 183 Hz vibrating wire.

The responses of the 47 Hz vibrating wire as a function of drive force is similar to that of the 183 Hz vibrating wire, as shown in Fig. 3(a). The pair-breaking velocity for the 47 Hz vibrating wire is estimated to be 19 mm/s as same as that for the 183 Hz vibrating wire. Consequently, we conclude that the ratio of $v_p/v_L$ is 0.3, independent of oscillation frequency and $^3$He pressure. The simultaneous experiments, using the 47 Hz vibrating wire (generator) and the 183 Hz vibrating wire (detector), indicate that the velocity of the detector increases due to the screening effect at generator velocities above 11 mm/s, as shown in Figs. 3(a) and (b). Therefore the onset velocity $v_c$ of vortex emission for the 47 Hz vibrating wire is estimated to be 11 mm/s, which is lower than the pair-breaking velocity 19 mm/s. We also found that velocity data scatter above $v_c$, as shown in Fig. 3(a).

These results suggest that another mechanism of vortex emission arises for the 47 Hz vibrating wire. One possible reason is that turbulence is caused by pair breaking in local flow enhanced by protuberances on the surface of the wire [12]. Pair breaking induced by the enhanced local flow causes plateaus due to vortex nucleation in the velocity responses of the vibrating wire as a function of drive force. However, we did not observe plateaus in the velocity responses of the 47 Hz vibrating wire as shown in Fig. 3(a), implying that a mechanism of vortex emission is different from that in the previous study.

Another possible reason is that the vortex emission is caused by instability of remanent vortices.
attached to the wire, as observed in superfluid $^4$He study [6]. The critical velocity of the turbulent transition in superfluid $^4$He was observed to be 23 mm/s for a 100 Hz vibrating wire in our recent work and 19.5 mm/s for a 120 Hz oscillating sphere[13]. These velocities are not so different from the onset velocity 11 mm/s observed for the 47 Hz vibrating wire, implying vortex emission due to remanent vortices. Further experimental and theoretical works are necessary to clarify the mechanism of the turbulent transition.

4. Conclusion
We reported vortex emission by a vibrating wire with a low resonance frequency in superfluid $^3$He-B at 28 bar. The onset velocity of vortex emission for a 183 Hz vibrating wire is higher than a pair-breaking velocity, indicating that vortex emission is caused by pair breaking. In contrast, the onset velocity for a 47 Hz vibrating wire is lower than the pair-breaking velocity. These results suggest that another mechanism of vortex emission arises for the 47 Hz vibrating wire: vortex emission is caused by pair breaking due to local flow enhanced by protuberances on the surface of the wire, or by instability of remanent vortices attached to the wire. A low-frequency vibrating wire is useful for investigating the transition to turbulence in superfluid $^3$He-B.

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