Laminar–Turbulent Transition Generated by an Oscillating Object in Superfluid $^4$He

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Abstract. The transition to turbulence in boundary flow of superfluid $^4$He is investigated using a vibrating wire. An object in a superfluid can easily generate the turbulence by oscillation even at very low temperatures, because remanent vortices are attached to it from the beginning. However, these vortices affect the transition to turbulence, occasionally causing intermittent switchings between laminar and turbulent flows. Recently, we have successfully devised a condition of vortex-free superfluid, in which a vibrating wire cannot generate turbulence. This condition prevents an oscillator from the switchings, enabling us to study the transition from turbulent to laminar flows. Using a vortex-free vibrating wire and a generator of vortex rings, we find that a turbulent state has a lifetime at driving forces near the transition, while it seems to be permanent at high driving forces. Lifetime data scatter widely, suggesting that the transition from turbulent to laminar flows is a probability event.

1. Introduction
Quantum turbulence generated by an oscillating object in superfluid helium has been recently attracted research interest in response to new investigations at very low temperatures (see Ref. [1] and references therein). In experiments, an oscillating object with a simple shape, such as a sphere or cylinder, is useful for experimental studies of turbulence in superfluid $^4$He [2, 3, 4]. The responses of the oscillator exhibit a sharp transition between laminar flow (more precisely potential flow) and turbulent flow as a function of driving force. The transition usually exhibits hysteresis, suggesting that the mechanism of the transition from laminar to turbulent flows is different from that of a transition in the opposite direction. Intermittent switchings between the two states are also frequently observed [5, 6]; however, they make it difficult to study the transition. In a recent study [7], we reported that remanent vortices forming bridges between an oscillator and a surrounding wall cause the transition to turbulence. We also reported that vortex rings can trigger the turbulence for a “vortex-free” vibrating wire that was unable to generate turbulence [8]. Thus, the presence of vortex seeds can cause turbulence for an oscillating object. In this paper, we concentrate on the transition in the opposite direction, from turbulent to laminar states, using a vortex-free vibrating wire. The vortex-free condition prevents a vibrating wire from the intermittent switchings, enabling us to study the mechanism of the transition from turbulent to laminar flows.

2. Experimental setup
The experimental setup consisted of two vibrating wires, similar to those described in a previous paper [8]. Superconducting wires (NbTi) with a 3 $\mu$m diameter were formed into semicircles. The wires were located in a small chamber with a 0.1-mm-diameter pinhole. One of the wires (labelled A) was oriented so that it pointed towards the centre of the other wire (B), perpendicular to its semicircle face. The
distance between the arms of a wire was 1.6 mm for wire A and 1.8 mm for wire B. The wires and the chamber were located in a cell in a magnetic field of 25 mT. The resonance frequencies of wire A and B are 1590 Hz and 1030 Hz in vacuum, respectively. We filled superfluid $^4$He cooled below 100 mK into the cell over 48 h. After filling, we observed that wire A was unable to generate turbulence and wire B was able to generate turbulence. In a turbulent state, an oscillating object emits free vortex rings [9]. Therefore, we used wire A as a detector of the transition and wire B as a generator of vortex rings.

3. Results and discussion
In a previous paper [8], we reported that vortex rings can trigger turbulence for a vortex-free vibrating wire. We performed experiments as following steps: (1) the driving force of the detector was increased to a certain value; (2) during keeping driving force, vortex rings were injected from the generator to the detector; (3) shortly afterwards, the detector entered a turbulent state. Even after stopping the generator, the velocity of the detector kept a low value. In Fig. 1, we show a typical case of the response of the detector in the turbulent state. As the driving force was reduced, the velocity of the detector remained low until it jumped to a high velocity equal to the initial value observed before the transition to turbulence. This velocity jump indicates the transition from turbulent to laminar states. While the generator was not vibrating, we further increased the driving force of the detector and found that the detector’s velocity traces the initial values observed before the transition and no transition to turbulence appears in the responses of the detector. Though the detector created many vortices in a turbulent state, these vortices were unable to affect the condition of the detector.

In the case shown in Fig. 1, we applied vortex rings to the detector oscillating at a driving force of 1 nN. After stopping the generator, the oscillation of the detector keeps a turbulent state at 1 nN, and we did not observe the transition to a laminar state in measuring time over 1 h. The turbulent state seems to be permanent at 1 nN; however, we observed the transition to a laminar state if the detector oscillates at 0.1 nN, as shown in Fig. 2. Experiments were performed as following steps. At the beginning, we generated vortex rings by the generator, to enter the detector oscillating at 0.1 nN into a turbulent state. After keeping this condition for 60 seconds, we stop the generator as shown in Fig. 2(a). The time in Figs. 2(a) and (b) is scaled at the stop of the generator. During stopping generation of vortex rings, the detector remained in a turbulent state, until it entered a laminar state, as shown in Fig. 2(b). The lifetime $\tau$ of the turbulent state is estimated to be 15 s in this case.

We also measured a delay time at a transition in the opposite direction, from laminar to turbulent flows, by a similar method [10]. The delay time, from the start of vortex-rings generation to the start of the transition for the detector, is estimated to be the order of 10 ms, three orders shorter than the lifetime observed here. In this transition, vortex rings propagate from the generator to the detector.
through surrounding superfluid, attaching to the detector and causing turbulence. Therefore, the delay time corresponds to the time of flight of vortex rings which caused turbulence for the detector. However, the lifetime is much longer than the time of flight of vortex rings, indicating that the mechanism of the transition is different from that of a transition in the opposite direction.

We measured the lifetime several times and found that lifetime data scatter from 0.2 s to 64 s in spite of the fixed driving force of 0.1 nN for the detector, as shown in Fig. 3. The scatter of the lifetime is expected to reflect vortex motions in the turbulent state. In a previous paper [8], we reported the motions of vortex lines against an oscillator forming sphere, initially in a vortex-free state, by numerical simulations. A vortex ring injected from a generator collides to the oscillator, splitting up into several segments. Large vortex segments attached to the oscillator may be stretched by oscillator motion, forming tangle in the path of the oscillator. The oscillator collides to the vortex tangle many times, eventually keeping the turbulent state with no supply of further vortices. In a steady turbulent state, a turbulent region remains in the path of the oscillator. The oscillator injects energy into the turbulent state by stretching vortex lines, while vortex rings depart from the turbulent region. Since large vortex rings cannot depart from the path of the oscillator before colliding to it, only small vortex rings, and therefore are capable of rapid, may depart from the turbulent region. Consequently, the dissipative structure in this system relates to the process of stretched vortex lines converting into the small vortex rings that can depart from the turbulent region. Quantitative discussion such as vortex line density is necessary to understand the lifetime observed here, though the steady turbulent state generated by an oscillating object has not been studied quantitatively yet.

At the transition to the laminar flow state, the vibrating wire is expected not to collide to vortex rings or stretch vortex lines attached to it. The absence of vortex lines in the path of the oscillator is considered to be accidental. Similar behaviours have been investigated using an oscillating sphere in superfluid helium [5]. Switchings between laminar and turbulent flows occurred frequently for the oscillating sphere. Observed lifetime data of a turbulent state scatter widely and exhibit an exponential distribution, suggesting a statistical fluctuation of vortex lines in the turbulent state. In the present study, we also observed the wide scatter of the lifetime of the turbulence state. The histogram of the lifetime

**Figure 2.** Time series of velocity of (a) the generator and (b) the detector oscillating at a driving force of 0.1 nN after stopping the generator. The time is scaled at the stop of the generator and the arrow in Fig. (b) indicates the lifetime $\tau$ of the turbulent state for the detector.

**Figure 3.** Histogram of the lifetime $\tau$ measured at 0.1 nN. The measurements were performed over 100 times for a driving force of 0.1 nN (see text). Lifetime data scatter from 0.2 s to 64 s.
shown in Fig. 3 is similar to those observed in the previous study. Consequently, the scatter of the lifetime is caused by a fluctuation of vortex lines in the turbulent state, suggesting that the transition is a probability event. The lifetime also seems to depend on energy injected by the detector oscillation. Further experimental and theoretical works are required to understand the transition to laminar flow.

4. Conclusions
We reported the transition to laminar flow in superfluid $^4$He using a vortex-free vibrating wire. Slow filling and a filter prevent vortices from attaching to the wire, and therefore prevent a vibrating wire from switching between laminar and turbulent flows. Using the vortex-free vibrating wire and a generator of vortex rings, we found that a turbulent state has lifetime whose data scatter widely. Histogram of the lifetime suggests a statistical fluctuation of vortex lines in the path of the vibrating wire, though the dissipative structure in the turbulent state has not been clear yet.

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