Repetitive Single Vortex-Loop Creation by a Vibrating Wire in Superfluid ^{3}He-B

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Spectacular features are observed on the velocity-force characteristics of a vibrating wire resonator in superfluid ^{3}He-B at ultralow temperatures. Both plateaus and discontinuities are seen in the characteristics. The plateaus seem to have two separate critical velocities where first some "event" occurs, which causes the wire to lose energy and slow down, followed by a second lower critical velocity where the event decouples. It is suggested that these events are due to vortex-loop creation at protuberances on the vibrating wire. This opens up the possibility of controlling the creation of vorticity through specially prepared protuberances.

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Since the Cooper pairs in superfluid ^{3}He are characterized by a total spin angular momentum $S = 1$ and total orbital angular momentum $L = 1$, the superfluid order parameter is correspondingly complex, giving rise to a large number of possible superfluid phases with different symmetries. Given the complexity of the condensate, there is also a range of topological defects associated with each phase. One such defect is the macroscopic quantum vortex.

There have been three main means by which vorticity has been studied in superfluid ^{3}He. In the rotating superfluid the counterflow built up by the rotation of the normal component is relaxed by the creation of a regular lattice of vortices which can be detected by their NMR signatures [1,2], ion focusing [3], or by mutual friction [4]. Vortices can also be created, apparently via the Kibble mechanism [5], as the liquid quenches rapidly through the superfluid transition after the intense local heating of the liquid following a neutron capture process [6,7]. Finally, vortices can be cyclically created during the oscillatory flow which is set up when superfluid is forced to flow through an orifice (weak link) [8,9]. The large phase gradient set up at the orifice can be relaxed by the generation of a vortex loop at the walls which when dragged across the orifice by the flow field removes 2π of phase from the phase difference across the orifice.

The present paper reports the repetitive creation of vortices by an oscillating wire loop in the superfluid B phase. The configuration of a wire moving through the superfluid is in some sense the inverse of the motion of the superfluid through a weak link and many of the phenomena observed have analogies with those seen in superfluid SQUIDs.

The experiments are made in a nuclear cooling stage of the Lancaster double cell style. The outer cell volume, filled with liquid ^{3}He and copper powder refrigerant, cools to around 0.7 mK at 0 bar and acts as a guard for the inner cell. The inner experimental volume is filled with liquid ^{3}He together with refrigerant in the form of copper plates coated with sintered silver powder for good thermal contact. This arrangement allows the superfluid in the experimental volume to be cooled to around 100 μK where the quasiparticle excitation density is extremely low. Temperatures below 150 μK ($T/T_c \leq 0.14$) are essential for the phenomena reported in this paper to be observable.

The moving wires are made in the form of our standard "vibrating wire resonators" in which a thin superconducting filament is bent into an approximately semicircular loop with the ends secured by gluing through a nonconducting plate. The loop has a mechanical resonance perpendicular to the loop plane. The frequency of the resonance is determined by the stiffness, mass, and geometry of the wire loops. In the case of the wires commonly used this varies from ~100 to ~1400 Hz. The superfluid has very low density and also a very low density of quasiparticle excitations, rapidly varying with temperature as $\exp(-\Delta/kT)$, where Δ is the superfluid energy gap. In order to probe the liquid hydrodynamics, the wire must be as thin as possible so that the internal friction in the wire is small compared to the effect of the liquid. In these experiments a typical resonator has a loop diameter of a few millimeters and a wire diameter of a few microns to just under 1 μm. These are constructed from various commercial copper matrix and Cu-Ni matrix filamentary wires which yield filaments in the range 4 to 15 μm. The matrix is chemically removed and the exposed filaments cut until one remains. The smallest filament used here has a diameter of just under 1 μm taken from a 30-filament wire specially made by Outokumpu Superconducting Wire Division, Finland.

The resonator is exposed to a small magnetic field in the plane of the loop and the resonance is driven by an ac current of the appropriate frequency passed through the loop. The Lorentz force on the current from the crossed field provides the drive. If the loop is arranged to be superconducting then there is no Ohmic voltage and (ignoring the small inductive voltage) the only voltage generated across the loop is that induced by the velocity in the field. The superconductivity thus decouples the drive (current) from the velocity response (voltage). rf-SQUID preamplifiers are used as the velocity induced voltages are small [10].

The phenomena observed are features of the velocity-drive characteristic of a resonator. This is recorded by

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slowly ramping the amplitude of the driving current and monitoring the velocity response at resonance. The overall shape of the resulting velocity-force curve is well understood [11]. Because of the unusual dispersion curve of the quasiparticle excitation gas and the Andreev scattering process, the force on an object moving with velocity v in the superfluid takes the form $F \propto kT \exp(-\Delta/kT)[1 - \exp(-p_F v/kT)]$. In the low velocity regime ($p_F v \ll kT$), this gives a force linear in velocity, proportional to $\exp(-\Delta/kT)p_F v$. With increasing velocity the damping force falls below this linear variation and finally becomes independent of velocity when $p_F v \gg kT$. With increasing drive force the peak velocity of the oscillating wire increases more and more steeply until it reaches a peak velocity ($\sim 9 \text{ mm s}^{-1}$) sufficient to cause pair breaking in the superfluid. At this point the damping increases extremely rapidly, giving an almost drive independent velocity. This general form of the velocity-drive characteristic shown in the inset of Fig. 1 is that which is seen with fairly robust wires, say, of order 100 μm in diameter. In the response of the very thin wires other features often appear overlying this general shape.

The main part of Fig. 1 shows the curves generated by a resonator made of the sub 1 μm wire. As can be seen there occur a number of plateaus where the velocity of the wire is limited and can pass only to higher velocities when the drive is significantly increased. At even higher velocities there also occur a number of discontinuities where the velocity suddenly drops with increasing driving force. This paper concentrates on the behavior on the plateaus.

Figure 1 shows curves taken over a (fairly narrow) range of temperatures; the various curves are much displaced since the background quasiparticle damping is a rapid function of temperature [varying, as pointed out above, as $\exp(-\Delta/kT)$]. The plateaus are broadly independent of temperature and can be followed as the temperature rises until swamped by the rapidly increasing quasiparticle damping. These plateaus are very reminiscent of those associated with phase-slip centers seen in the current-voltage curves in long superconducting weak links.

This behavior was examined more closely in a later experiment with somewhat thicker wires where the time resolution was better. Figure 2 shows the velocity-drive curve for a 4.5 μm diameter wire oscillating at 890 Hz at a temperature of 114 μK where the width of the resonance is 0.18 Hz. Again there are plateaus and discontinuities. This curve was measured slowly, over a period of 1.5 h, with a considerable smoothing time constant (300 ms) on the detection electronics (as was the case in the earlier experiment with the sub 1 μm wire) so that any rapid velocity change is invisible. When this electronic smoothing is removed, interesting features appear. Figure 3 shows the plateau at a peak velocity of 5.1 mm s^{-1} (labeled A in Fig. 2) taken at high time resolution plotted as a function of *time* as the drive is linearly increased. The plateau is no longer "flat" but consists of a series of pulses limited by two apparent "critical velocities." The slight decrease in the critical velocities over the measurement period is not understood but it is not due to warming during the sweep. Figure 4 shows an expanded view of the time evolution of the beginning and the end of this plateau. In the center of the plateau, the "pulse" shape is approximately triangular. Similar behavior is observed on the other clear plateau, at a peak velocity of 7.5 mm s^{-1} (labeled B in Fig. 2).

Figures 3 and 4 show that as the drive is ramped the peak velocity smoothly increases until a critical velocity v_{c1} is first reached. At this point the effective damping suddenly increases and the velocity rapidly falls until at a second lower velocity v_{c2} the extra damping vanishes as suddenly as it appeared. The velocity then rises again (more rapidly

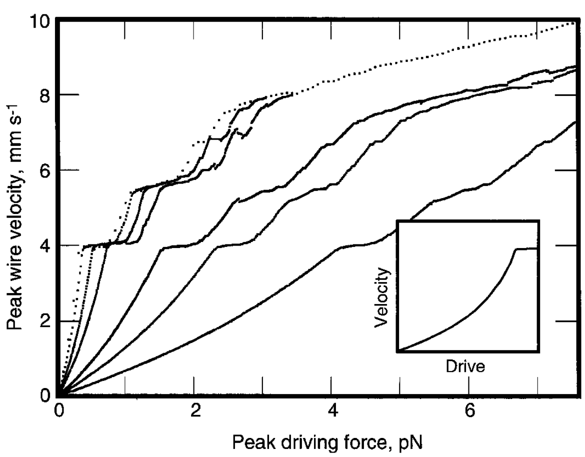

FIG. 1. Force-velocity characteristics for sub 1 μm vibrating wire resonator in superfluid ^{3}He-B over a range of temperature from 110 to 150 μK. The inset shows the characteristic expected for a relatively thick wire. The sharp change in slope occurs at the onset of pair breaking.

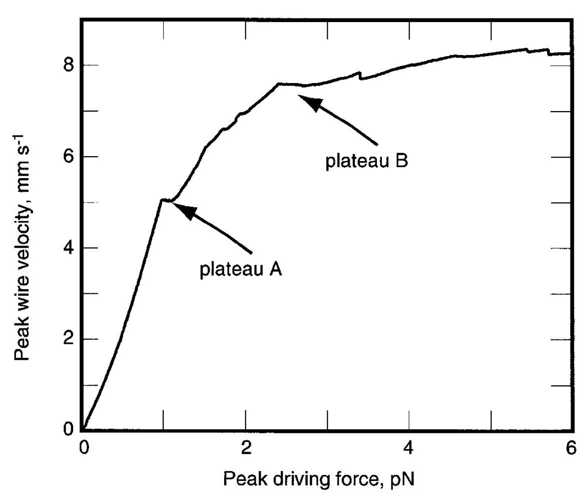

FIG. 2. Force-velocity characteristics for a 4.5 μm vibrating wire resonator at a temperature of 114 μK. Several plateaus and discontinuities are clearly visible.

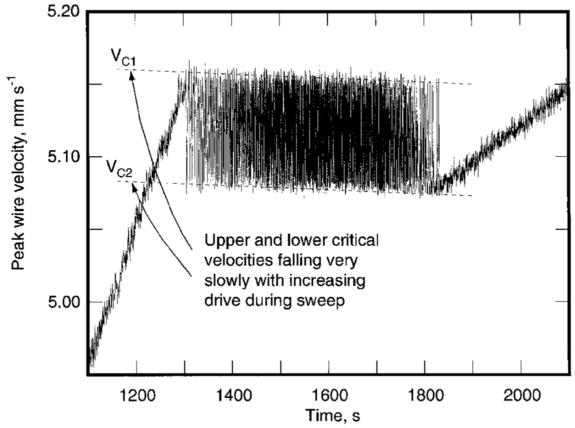

FIG. 3. The peak wire velocity as a function of time during a linear drive force sweep across the plateau labeled *A* in Fig. 2. The two critical velocities are clearly seen.

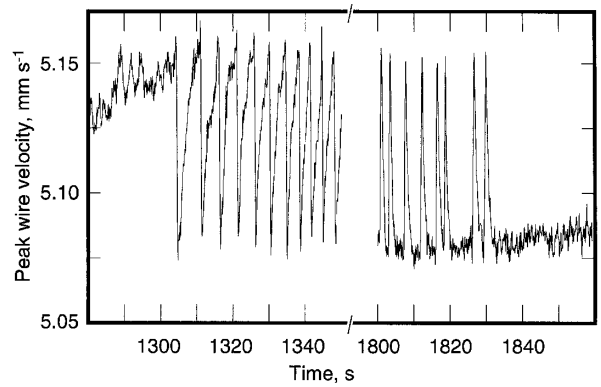

FIG. 4. An expanded view of the pulses at the start and end of the plateau shown in Fig. 3. The change in shape of the pulses is clearly visible. In the center of the plateau, the shape is approximately triangular.

this time since the drive force is now larger) until again v_{c1} is reached and the cycle starts once more.

This process repeats with increasing drive until after an event at v_{c1} the drive becomes high enough that the velocity is not allowed to fall to v_{c2}, and thereafter the velocity slowly increases and no further sudden damping events occur. At this point the plateau has been crossed after which the velocity again increases steadily with increasing drive but with a shallower slope than that below the plateau, indicating the existence of an additional dissipation mechanism.

When the driving force is slowly reduced from above the plateau, a similar time reversed picture is seen. As the velocity reaches v_{c2}, the damping vanishes and a rapid increase in velocity occurs until v_{c1} is reached, where the damping suddenly reappears and the wire slows back to v_{c2}. This continues until the drive is too small to allow the velocity to rise to v_{c1}. The velocity then follows the curve below the plateau as the drive continues to be reduced. The two critical velocities increase slightly with decreasing drive during this sweep.

The stability of the jumps between v_{c1} and v_{c2} is quite spectacular. If the drive is halted on the plateau the pattern simply repeats with time for hour after hour. The whole plateau can be traversed in this way if the drive is set at a point where the velocity lies just above the plateau, then, as the liquid slowly warms and the quasiparticle density (and therefore damping) increases with it, the plateau region moves very slowly through the set drive point.

The simplest picture of this behavior is that the moving wire produces vortex loops attached to the wire. One should emphasize that these wires are anything but perfect cylinders. The commercial filamentary superconducting wires from which a single filament is extracted are made by extrusion of a large billet of starting material. The extruding process gives rise to large striations on the interface between the filaments and matrix with the result that the filaments have a very irregular cross section. The process of extracting the single filaments is also inherently dirty, involving chemical etching and manipulation of the filaments with a pair of tweezers. The result is that the final single filaments used to make the vibrating wires are neither locally smooth or necessarily clean of fine debris. When the filament moves through the superfluid the flow velocity over any protuberances is locally increased, and at some critical value (our upper critical limit v_{c1}) the velocity becomes so large that the superfluidity breaks down locally, perhaps with the production of a vortex loop. Given the small size of these protuberances, one would expect that these critical velocities would be a substantial fraction of the wire peak critical velocity as is indeed seen.

As the loop grows, the energy needed for its production is extracted from the kinetic energy of the wire and the wire velocity falls. The loop grows until it detaches at the lower critical velocity. The loss in kinetic energy can be deduced from the measurements of v_{c1} and v_{c2} together with the properties of the wire. This indicates that $\sim 8 \times 10^{-17}$ J is extracted from the motion of the wire for each pulse along plateau *A*. The energy per unit length of a vortex loop is $\rho/4\pi(h/2m_3)^2\ \ln(b/\xi_0)$ [12], where ρ is the fluid density, m_3 is the ^{3}He atomic mass, and ξ_0 is the zero temperature coherence length ($\sim$65 nm at 0 bar). The parameter b represents the extent of the flow field around the vortex. Taking this to be 1 mm, although the result is insensitive to this choice, suggests that a vortex length of order 0.3 mm would account for the lost energy.

The intriguing question is why the loops detach or are destroyed at the second critical velocity. Since the peak velocity of the wire for the initial pulse in Fig. 4 takes $\sim$0.3 s to fall to the lower critical value, the growth process continues over many cycles of the wire oscillation although this may be limited by the response time of the resonator. At this point the vortex decouples from the wire, the wire now travels without the extra damping, and the wire's velocity rapidly increases again to the upper critical velocity, whereupon the process repeats. The mechanism for decoupling is not understood. The moving wire generates a complex flow field in which the vortex moves. Whether the decoupling is due to the ends of the vortex loop being able to meet each other only at a lower wire velocity or to the creation of a vortex with the opposite sign is not clear.

A simple phenomenological model of the process explains the change in the shape of the pulses as the plateau is traversed (shown in Fig. 4). This model assumes that the dissipation of the wire has two natural stable situations. These are the low dissipation regime below the plateau and a high dissipation regime above the plateau region. (Similar two state behavior has been observed in superfluid ^{4}He with vibrating microspheres [13] and with vibrating wires [14].) As the velocity increases from below the plateau, the wire continues in the low dissipation state until v_{c1} is reached for the first time, at which point it switches towards the high dissipation state possibly with the formation of a vortex loop. As the equilibrium velocity in this state is considerably lower than the current velocity, and well below v_{c2}, the velocity rapidly falls until v_{c2} is reached. At this point, our presumed vortex decouples, the wire switches to the low dissipation state, and the velocity increases back to the new equilibrium velocity for this drive level. Since this would be just slightly greater than v_{c1}, the rate of change of the velocity is much lower than on the initial fall. Towards the end of the plateau (the right-hand side of Fig. 4) the situation is reversed. The low dissipation state equilibrium velocity is now well above v_{c1} so that the wire velocity rapidly increases as the vortex decouples at v_{c2}, while the subsequent fall following reaching v_{c1} is much slower since the equilibrium state is not far below v_{c2}. Eventually, the equilibrium velocity in the high dissipation state becomes greater than v_{c2} and pulsing ceases.

The multiplicity of plateaus seen on the various wires indicates that there are several active protuberances which all behave broadly in the same way but with different and independent critical velocities. This is confirmed by the fact that the positions of the plateau velocities are completely reproducible from run to run and even after cycling to room temperature, provided the resonator is not disturbed, and further confirmed in that we have never been able to find any relationship between the various plateau velocities which appear to be completely randomly distributed.

In conclusion, this experiment suggests that vorticity can be produced in a regular and detectable manner by moving a wire resonator through superfluid ^{3}He. Since such resonators are inherently simple, this technique opens up the possibility of observing the vorticity created by the controlled movement through the superfluid of prepared protuberances, electropolished tips, for example, as well as by more complex multiply connected shapes such as fine loops.

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