Landau Critical Velocity for a Macroscopic Object Moving in Superfluid ^{3}He-B: Evidence for Gap Suppression at a Moving Surface

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We have observed that the motion of a vibrating-wire resonator in superfluid ^{3}He-B at temperatures below $T_c/8$ is associated with a sharp critical velocity, v_c, above which very high dissipation sets in. We identify this velocity with the Landau critical velocity for pair breaking. That the observed value of v_c is a factor of 2 lower than the critical velocity expected from the BCS value of the gap we take as evidence that the gap is suppressed by about 50% of its bulk value near a moving boundary.

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One of the characteristic properties of a superfluid is the existence of a critical velocity, v_L, below which the creation of elementary excitations is not possible. In principle a body should be able to move frictionlessly through the condensate at zero temperature until v_L is reached and dissipation processes set in. In practice it has been found impossible to achieve the necessary velocities with anything but microscopic objects. In He II an alternative dissipation mechanism can operate at lower velocities through the creation of vortices, and the Landau limit has only been reached over a limited range of temperatures and pressures by microscopic projectiles in the form of negative ions.[1,2] In the case of ^{3}He the superfluid is embedded in a highly dissipative quasiparticle gas which conspires to mask any mechanical probing of a critical velocity, and again behavior appearing to show a Landau velocity has only been observed in the case of ions.[3,4] The inverse process, the flow of superfluid through a stationary channel, again shows dissipation in He II at much lower velocities because of the generation of vorticity, but critical currents apparently associated with pair breaking have been observed in ^{3}He-B in the Ginzburg-Landau regime.[5,6] Here, however, the measured quantity is a critical volume current which contains not only a velocity but also the superfluid fraction.

In the experiments reported here we have studied the motion of two wire resonators in ^{3}He-B at very low temperatures. The precise temperature is unknown, since we are able to cool the liquid below the limit of our various thermometers. In this temperature regime, where the quasiparticle density is essentially zero, pair-breaking effects manifest themselves as a very clear critical velocity in the motion of the wire.

We have investigated this behavior using two very different vibrating wires in various magnetic fields and at three different pressures. The results are very clear-cut: The maximum velocity of a light vibrating wire cannot significantly exceed a critical velocity even when the driving force is increased by two orders of magnitude. This critical velocity has the same magnitude for the two wires we have studied which differ in diameter by a factor of 10. From a comparison of the results at different pressures this critical velocity is found to be very accurately proportional to the Landau critical velocity, Δ/p_F, but its magnitude (about 8 mm/s for 0 bar) is smaller than the straightforward Landau value (30 mm/s for 0 bar) for reasons which we discuss below.

We propose that the behavior provides direct evidence of a Landau critical velocity in ^{3}He-B for the motion of a macroscopic object, and thus constitutes the first observation of such a limit in any superfluid. Further, we believe that the mechanism operates through the creation of quasiparticle pairs in the immediate vicinity of the moving boundary, where we find that the gap is suppressed to a level of around 0.5 of its bulk value.

The operation of the vibrating-wire resonators has been described elsewhere.[7] Briefly, the two resonators are situated in the inner cell of a double-cell demagnetization experiment similar to that described by Bradley *et al.*[8] The resonators are approximately 8-mm-diam semicircles of wire, anchored at the ends, and exposed to a steady magnetic field in the plane of the loop. The wires used for the present measurements are a 13.5-μm-diam NbTi filament and a 0.124-mm-diam Ta wire. The resonators have a low-lying mechanical mode in which the loop oscillates in a direction perpendicular to its plane (at 347 Hz for the filament and 747 Hz for the Ta wire). This resonance can be excited by the Lorentz force on an ac current of appropriate frequency fed along the wire. The velocity of the movement excited, v, is inferred from the voltage generated, $V = vBl$, where l is the effective length of the wire normal to the field (there being no Ohmic voltage from the driving current, since the wires are superconducting). Under the control of a Hewlett-Packard model 85 desk-top computer, the excitation current is generated by an HP 3325A synthesizer which steps slowly through the resonance. The output voltage is detected by an EG&G/Brookdeal 5206 lock-in amplifier. The lock-in amplifier is used in the r, θ mode, where the r-channel output gives the rms value of the absolute magnitude of the output voltage from the wire, $|V|$. This value of voltage is converted to the maximum instantaneous velocity, v_m, of the wire through the relation $v_m = \sqrt{2}K|V|/Bl$, where the factor $\sqrt{2}$ comes from the time variation of the velocity (rms to peak), and K is a factor which relates the average to maximum spatial variation of the wire velocity. A semicircular wire flexing at its supports would give $K = 4/\pi = 1.27$. We estimate that for our geometry, $K = 1.2 \pm 0.1$.

On demagnetization of the experimental cell the helium cools to a temperature below $0.13T_c$. In this regime the normal-fluid density is very low, and the damping of the wires from this source is negligible. At low drive levels the line shapes are approximately Lorentzian (the Ta wire tends to have a rather asymmetric line, but in the present context that is not a problem). As the drive level is increased, the peak velocity of the wire increases, until a critical velocity (corresponding to a critical output voltage) is reached. It is almost impossible to drive the wire to significantly higher velocities, whatever the level of the driving force. This behavior is manifested by the abrupt truncation of the Lorentzian line shape of the resonator at a voltage amplitude corresponding to the critical velocity.

In Fig. 1 is plotted the response of the 13.5-μm resonator for various levels of drive current at 0 and 12.1 bars in a field of 25 mT. The logarithm of the maximum instantaneous velocity of the wire, v_m, is plotted against frequency. For a linear system, the line shape should remain unchanged, simply translating uniformly to higher velocities as the drive level is increased. The critical velocity at which the line shape is truncated is quite evident. The maximum velocity is not completely rigid, and some breakthrough is observed, but the maximum only increases by a few tens of percent for a factor of 100 increase in drive level.

Figure 2 is essentially a section through Fig. 1. The figure shows the peak value of v_m plotted as a function of drive level for 0, 4.15, and 12.1 bars. Also plotted is the onset value of v_m at which deviation from Lorentzian behavior is first detected and which we identify as the critical velocity, v_c. This value is readily identified in the r, θ mode, being associated with the onset of a rapid change in phase, and corresponds to the shoulder seen in Fig. 1. A similar plot of v_m can be made for the 0.124-mm Ta-wire resonator. To

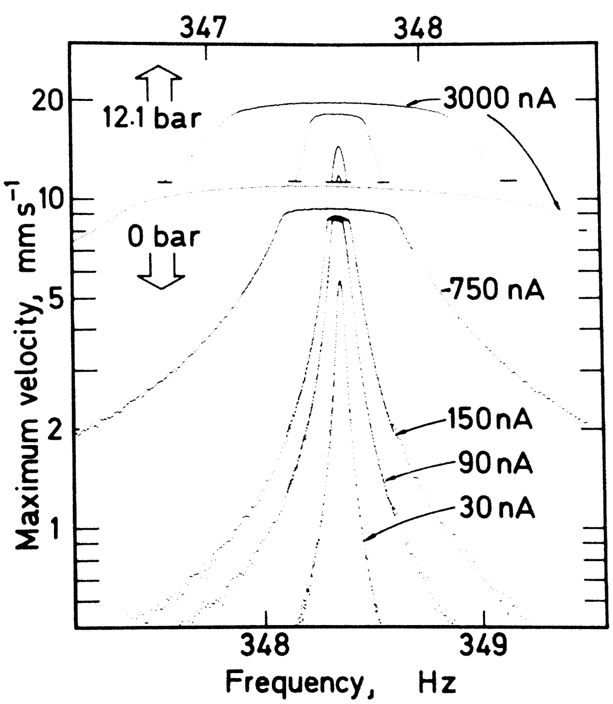

FIG. 1. Velocity response of the 13-μm-wire resonator in ^{3}He-B at two pressures at $T < 0.13T_c$. The logarithm of the maximum instantaneous velocity is plotted against frequency. The 12.1-bar data are slightly displaced in frequency as the resonance is shifted down by 0.625 Hz because of the higher liquid density. The truncation of the velocity at a critical value is clearly seen, as also is the fact that this velocity is a function of the pressure. Below the critical velocity the quasiparticle damping is negligible, and the width seen in the figure arises almost entirely from the vacuum damping of the wire alone, and thus the two sets of data can be superimposed in this region.

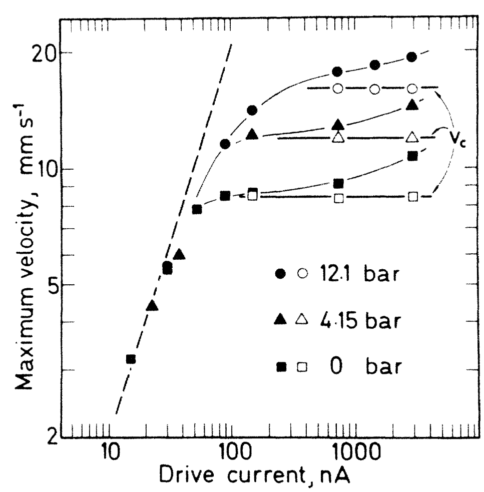

FIG. 2. Maximum instantaneous velocity of the 13-μm-diam resonator as a function of drive level for three different pressures. Filled symbols represent the peak of the resonance. Open symbols represent the onset velocity at which non-Lorentzian behavior is first detected. The dashed line represents a linear relation between velocity and drive. Bold horizontal lines mark the three critical velocities. The curved lines serve only to guide the eye.

bring the Ta wire up to similar velocities requires about a factor of 40 greater drive current than that needed for the filament. Since the Ta wire is larger in diameter and has a much higher density, the influence of the liquid is not so strong. The velocity cutoff is less sudden, and an onset velocity cannot be identified with any confidence from the line shape. However, the same critical velocity is observed to within the error of about 20%. The critical output voltage for both wires scales with applied field as expected.

It is interesting to speculate on what the motion of the wire should be like in the highly flattened regions at around the critical velocity seen in Fig. 1. We have examined the harmonic content of the wave form in these regions and find that in spite of the unusual frequency response, the wave form remains sinusoidal with less than 10^{-3} admixture of third harmonic. This is consistent with a sudden increase in damping at v_c, which can impulsively extract all the extra kinetic energy delivered by the drive to the resonator during the previous half-cycle without the maximum velocity of the wire having to exceed v_c by any measurable amount.

The existence of a critical velocity is immediately suggestive of a Landau condition. Landau's simple energy-momentum conservation argument gives a critical velocity $v_L = (E/p)_{min}$ for an excitation of energy E and momentum p created by a heavy object of velocity v_L in the superfluid. The equivalent quantity in ^3He for the breaking of a Cooper pair would be the velocity corresponding to the minimum value of E^*/p^*, where the starred quantities are the energy and momentum of the pair produced. This velocity is clearly $v_L = 2\Delta(0)/2p_F$, i.e., $\Delta(0)/p_F$. The measured values for the critical velocity at the three pressures are very closely proportional to the corresponding values of v_L as shown in Table I. The magnitudes of the velocities, however, are lower than the appropriate values of v_L by a factor of about 4.

We expect the measured maximum velocity to be lower than the Landau value. The Landau argument relates to the generation of excitations in a static fluid and also ignores the possibility of spatial variations of the energy gap. If we postulate that the energy gap is suppressed in the neighborhood of a boundary [say to $D\Delta(0)$], then there are two consequences. First, the energy required to create an initial pair of excitations is only $2D\Delta(0)$, and second, these excitations will be initially trapped in the energy well of the suppressed gap traveling with the wire. In the region of gap suppression within a coherence length, i.e., around 15 nm, of the wire, there will be essentially a continuum of bound single-particle states. In consequence, if the moving wire can directly break a pair into two bound quasiparticles with energy $2D\Delta(0)$, then subsequent scattering processes can promote the newly formed quasiparticles out of the well and into the bulk as shown schematically in Fig. 3. The only critical amount of energy required is thus the initial $2D\Delta(0)$.

In general we take the Landau condition as relating to the quantity $v_s - v_n$ for translational invariance. The initial trapping of the quasiparticles in the well at the boundary, which we can take as stationary with respect to the wire, suggests that in our geometry the Landau velocity should refer to the relative velocity between the wire and the superfluid in the vicinity. If we ignore possible influence of the texture, we expect the superfluid component to accommodate the motion of the wire by pure potential flow. The appropriate flow pattern around a moving cylinder yields a maximum relative velocity between wire and superfluid of twice the wire velocity along the two lines along the cylinder with normals perpendicular to the direction of motion. This gives an extra factor of 2 in relative motion between quasiparticles and superfluid, and thus we might expect $2v_c = 2D\Delta(0)/2p_F$, i.e., $v_c = Dv_L/2$. Values of D calculated in this way are shown in Table I and are close to 0.5 for all three pressures. If details of the directionality of the depression of the gap by the surface (which may well be averaged

TABLE I. A comparison of the calculated values of the Landau velocity, v_L, for the three pressures measured with the observed values of the critical velocity, v_c, and the derived gap suppression factor, D. The values of T_c are taken from Ref. 9 and those for p_F from Ref. 10.

Pressure (bars)	v_L $(=1.76kT_c/p_F)$ (mm/s)	$v_{c\,meas}$ (mm/s)	D $(=2v_c/v_L)$
0	30.5	8.4	0.55
4.15	44.4	12.0	0.54
12.1	59.3	16.1	0.54

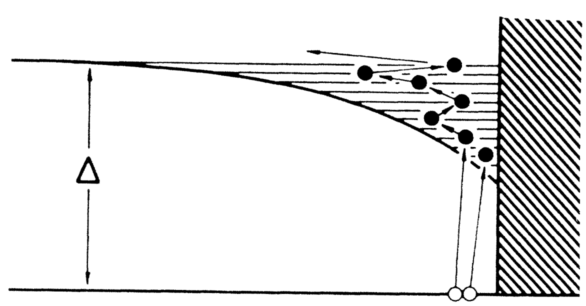

FIG. 3. Schematic diagram illustrating the pair-breaking mechanism. The gap is depressed near the (striped) wall (directional factors are ignored). A pair near the wall can be broken to give quasiparticles of energy less than Δ, which can be promoted into the bulk quasiparticle sea by subsequent scattering processes.

by surface roughness) are ignored, this observed reduction at an interface is in line with recent theoretical work.[11] However, the gap should be depressed not only by the static influence of the boundary but also by the flow field around the wire. Since we infer the depression factor from measurement at the observed critical velocity, we cannot distinguish experimentally between these two mechanisms.

The pair-breaking argument presented above is based on the assumption that the wire by some mechanism can break a Cooper pair directly. It is also possible that the process is mediated by an incoming quasiparticle, either real or virtual, which is scattered by the wire in such a way as to gain the minimum energy needed to break a pair, $2D\Delta(0)$. The critical wire velocity is the same in both cases, since the Landau criterion represents a numerical condition rather than being derived from a specific mechanism.

There is of course the possibility that the critical velocity is not a manifestation of pair breaking but instead reflects a textural transition to a dissipative state driven by the superfluid flow pattern around the wire. However, taking the A-phase dipole-locking length of a few tens of microns as a convenient comparative yardstick, we should expect the observed critical velocity to depend on the diameter of the wire for our wire sizes. However, as we noted above, no such dependence is seen. Further, we would not expect any such transition to be so closely tied to the value of $\Delta(0)/p_F$.

The bound, unpaired states form a two-dimensional gas of quasiparticles with energies less than the bulk value of the gap and are likely to show interesting directional properties. The present method may provide a useful probe for their study. These states should be rather important in heat exchange between ^{3}He and a boundary, especially at low temperatures when the bulk normal-fluid fraction is very low. It is interesting to note that our recent measurements[12] of boundary conductance between sintered silver and the B phase {where we expect the heat flow to contain a term in $\exp[-\Delta(0)/kT]$}, although not presented in these terms, are consistent with a gap for the heat-exchange process which is around half the bulk value.

It would be instructive to repeat the experiments with a much thinner filament, since the truncating effect ought to be even more effective. We have in the past made resonators with filaments 2 μm in diameter but have not had the confidence of their survival to incorporate them in a nuclear cooling cell. It would also be of interest to look at the rate of rise of force on the wire as the critical velocity is exceeded, i.e., to look at the "stiffness" of the pair-breaking process, especially with the use of much thinner wires, which can be driven to the critical velocity while dissipating much less heat in the liquid. Such supercritical experiments have yielded valuable information on the corresponding process in the case of ^{4}He.[13]

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