SUPERFLUID HELIUM

Caught speeding

A wire moving at constant speed through superfluid helium can considerably exceed the Landau critical velocity.

William P. Halperin

In his seminal work on the two-fluid hydrodynamics of superfluid helium Lev Landau established a fundamental limit to the velocity of the superfluid: the Landau critical velocity[1]. Superflow — dissipationless mass flow — around an obstacle or through a channel should not exceed this relative velocity. The existence of such a critical velocity is well documented for both superfluid ^{4}He and ^{3}He using flow and ion mobility studies, although approaching (or actually reaching) this limit depends on the specific physical structure of the object. Now writing in *Nature Physics*, Ian Bradley and colleagues show that the Landau critical velocity can be greatly exceeded by a wire moving in a fermionic condensate[2]: ^{3}He at very low temperatures in one of its superfluid phases.

In Landau's two-fluid theory the critical velocity is determined by the minimum energy that is required to create an elementary excitation. For ^{4}He this is the energy required to create a roton, an excitation with energy ΔE represented in the momentum dependence of the energy dispersion, $E(p)$, as shown in Fig. 1. Superfluidity breaks down when a moving object transfers energy to the fluid. This requires energy states E to be available at the requisite momentum p for which $E/p > (\mathrm{d}E/\mathrm{d}p)_{\min} = v_{\mathrm{L}}$, thereby defining the Landau critical velocity as in ref. 3. The Landau critical velocity is defined for bosonic or fermionic superfluids that have a gap in the excitation spectrum. The latter include superconductors and superfluid ^{3}He-B, for which ΔE occurs at the Fermi momentum and determines the minimum energy required to create a fermionic excitation out of the condensate of Cooper pairs.

In their experiment, Bradley and co-workers apply a controlled force to move a wire through the superfluid at a predetermined velocity. For sinusoidal motion the authors found an abrupt onset of dissipation with increasing speed, consistent with the existence of a critical velocity. This onset occurs at a wire speed of the order of $v_{\mathrm{L}}/3$, in agreement with a phenomenological theory that takes into account the fluid back-flow around the wire[4]. The mechanism is believed to involve the breaking of Cooper pairs on the wire surface where the superfluid energy gap is suppressed, thereby leading to the excitation of surface bound states. With each reversal of the motion, the energy of these bound state excitations is progressively pumped higher until quasiparticles are able to radiate into the bulk. However, in a parallel sequence of experiments, Bradley *et al.* drove the wire at a constant speed to find that larger velocities only require a modest increase in force with no evidence for an abrupt onset of dissipation, extending well above the Landau critical value.

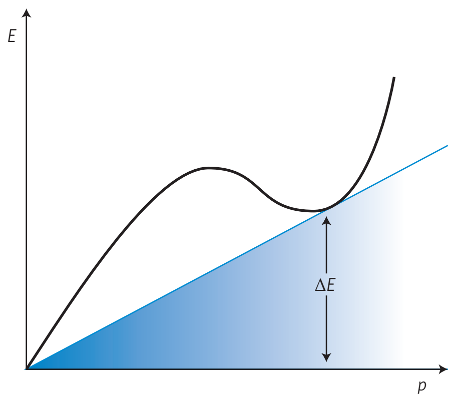

Figure 1 | Schematic of the energy dispersion, $E(p)$, for superfluid ^{4}He with a roton gap ΔE. The blue shaded region corresponds to a velocity (of the superfluid relative to a solid object) that is less than the Landau critical velocity given by the tangent line through zero.

So, why is there no critical velocity for a wire moving at constant velocity? The authors' suggested answer involves the surface bound states. For the steady-state case, after being driven out of equilibrium during acceleration, the bound state excitations can thermally equilibrate with the wire. And in the absence of additional pair-breaking during the time that the wire is driven at constant speed these excitations are blocked from radiating quasiparticles into the bulk superfluid, which would otherwise lead to dissipation.

It is clear that this observation of wire motion can provide important insight into the nature of the bound states at the wire surface. In ^{3}He-B the surface states are Majorana fermions — a subject of considerable current interest in the study of topological quantum matter[5]. For a deeper understanding and characterization of these states, theoretical work that takes into account the boundary conditions at the surface of the wire will be required. The situation for ion motion is simpler for two reasons: their smaller size compared with the coherence length and their perfect spherical shape. In fact, complementary work reports the results of mobility measurements of negative ion bubbles with diameters of 5 nm located just below the free surface of superfluid ^{3}He-A (ref. 6). The force on the bubble was shown to have a transverse component — either to the left or right — depending on the sign of the superfluid angular momentum normal to the surface: a direct indication of chiral symmetry of this superfluid phase. A new theory[7] in perfect agreement with that experiment raises expectations for further progress in fully understanding superfluid flow, or equivalently the motion of well-defined objects through a superfluid, expanding research into a new area of micro-superfluidics. ❐

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