Vortex-line avalanches in rotating superfluid ^{3}He-B

A.P. Finne [a,1], R. Blaauwgeers [a,b], V.B. Eltsov [a,c], N. Kopnin [a,d], M. Krusius [a], L. Skrbek [a,e]

[a] *Low Temperature Laboratory, Helsinki University of Technology, Box 2200, 02015 HUT, Finland*
[b] *Kamerlingh Onnes Laboratory, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands*
[c] *Kapitza Institute for Physical Problems, Kosygina 2, Moscow 177334, Russia*
[d] *Landau Institute for Theoretical Physics, Kosygina 2, Moscow 177334, Russia*
[e] *Joint Low Temperature Laboratory, Institute of Physics ACSR and Charles University, 180 00 Prague, Czech Republic*

Abstract

Vortex formation in rotating metastable vortex-free ^{3}He-B occurs at temperatures close to T_c in discrete events where a small number of initial loops is produced per event. These evolve to form a stable cluster of rectilinear lines in the center of the sample. Below $0.6\,T_c$ the behavior changes: some events produce a very large number of vortex lines such that the final state approaches the equilibrium configuration independently of the initial process by which the first vortex loops were formed. Below $0.5\,T_c$ all events behave in this way. We explain the crossover from linear to non-linear vortex loop expansion as an instability to turbulent avalanche-like vortex loop proliferation.

Key words: superfluid; helium3-B; vortex formation; mutual friction; turbulence; critical velocity; AB phase boundary

In superfluid ^{3}He-B, vortex-free flow can be maintained in rotation up to high normal-superfluid counterflow velocities as a metastable *Landau state*. The absolute upper limit for vortex-free superflow is the intrinsic critical velocity [1], but in practice often other sources of vortex formation intervene. We have identified a new non-equilibrium mechanism which brings about an avalanche-like proliferation of vortex lines as soon as some initial vortex loops have been formed. The new process is activated at temperatures below $0.6\,T_c$. It essentially removes all the excess vortex-free counterflow such that the final state is close to equilibrium solid-body rotation. We suggest that the new mechanism represents *turbulent vortex-loop expansion.*

In our experiment vortex formation is observed with NMR as a function of temperature in a standard measuring geometry where the ^{3}He-B sample is contained in a smooth-walled closed quartz cylinder (radius $R = 3$ mm). The thermal connection to the sintered heat exchanger is via a small orifice (diameter 0.75 mm) [2]. The measurements are performed by increasing the rotation velocity Ω at slow rate $\dot{\Omega} \sim 10^{-4}$ rad/s^2 at constant temperature.

Two sources of vortex formation can be compared: (i) The flow of vortices through the orifice from the heat exchanger volume to the sample space [3]. This *extrinsic* process is responsible for vortex formation when the sample consists of only B phase and the container wall is sufficiently smooth. In the present setup it controls vortex formation in the single-phase ^{3}He-B sample. (ii) When the phase boundary between the A and B phases is magnetically stabilized in the long cylinder [2], vortex formation in ^{3}He-B occurs via the shear flow instability of the AB interface [4]. In our measuring setup this process gives the most consistent data on the crossover to turbulent vortex-loop expansion with decreasing temperature.

Both vortex-formation processes have a characteristic critical rotation velocity Ω_c, which depends on temperature and other externally controlled parameters. The process with the lowest Ω_c then becomes responsible for the formation of vortices. At high temperatures, a limited number of vortex lines is formed when Ω_c is reached in slow acceleration at constant $\dot{\Omega}$. On cool-

[1] E-mail: antti.finne@hut.fi

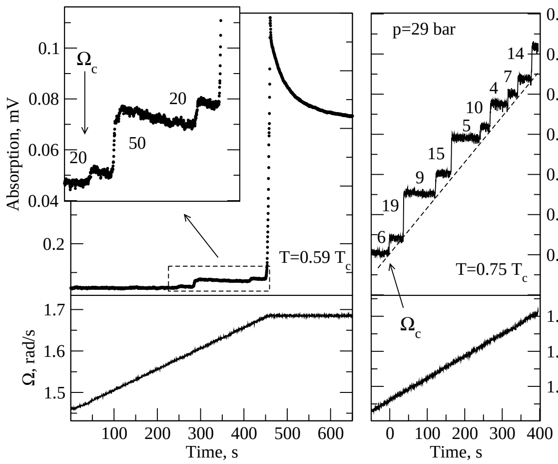

Fig. 1. Vortex-formation in the AB-interface instability with (left)/without (right) turbulent loop expansion. The NMR pick-up is tuned to the frequency of the Larmor edge, where the step-like increase is caused by the increase in the number of vortex lines ΔN. Its value is given at each individual step. The large increase in the left main panel corresponds to $\Delta N \approx 1200$. After this large step the slow relaxation at constant Ω represents the slow motions in the vortex array towards its equilibrium state and order-parameter texture.

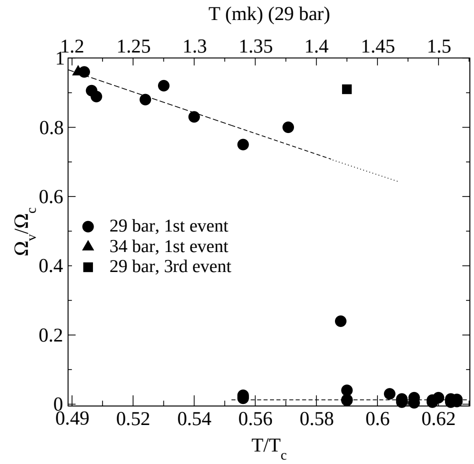

Fig. 2. The relative vorticity Ω_v/Ω_c, created in one instability event of the AB interface, in the crossover regime 0.5 — $0.6\,T_c$. Here Ω_c is (1.5 ± 0.1) rad/s. The measuring uncertainties are smaller than the size of the data points.

ing to lower temperatures, in the narrow temperature interval 0.6 — $0.5\,T_c$ the character of the vortex formation process is changed: The number of vortex lines ΔN created per event increases up to the maximum possible. Close to $0.6\,T_c$ this new feature appears randomly in a fraction of the processes, but below $0.5\,T_c$ all events behave in this way.

As shown in Fig. 1, above $0.6\,T_c$ the AB-interface instability (ii) produces a random burst of $\Delta N = 1 \ldots 30$ vortex lines. At lower temperatures more and more bursts approach the maximum possible vortex number, $\Delta N \lesssim \pi R^2 (2\Omega_c/\kappa)$ ($\kappa = h/2m_3$ is the circulation quantum). Below $0.5\,T_c$ all events are of this kind. The crossover from linear to non-linear loop expansion is illustrated in Fig. 2, expressed as the ratio between vorticity $\Omega_v = \Delta N \kappa/(2\pi R^2)$ and critical velocity Ω_c. The new nonlinear process does not control the onset of vortex formation since the AB-interface instability follows a smooth temperature dependence also in the crossover regime, as predicted by the Kelvin-Helmholtz (KH) theory [4]. Instead, the new process switches on afterwards during the expansion of the initial vortex loops and changes the final yield of vortex lines.

Above $0.6\,T_c$, the first burst of vortices through the orifice into the sample volume (i) occurs at a high Ω_c, which is constant in temperature and produces a limited number ΔN of vortex lines [3]. The counterflow velocity can then be increased to roughly the previous level before the next burst sets in. In the crossover range 0.6 — $0.5\,T_c$ this situation becomes unstable and changes in character: Ω_c drops to a low value, which now depends on the rotation noise spectrum and $\dot{\Omega}$. Secondly, after the burst the final state is one with almost the equilibrium number of vortex lines.

In our long sample vortex loop expansion can be associated with a flight time τ_F. If one measures Ω_c at different steady values of rotation acceleration, $\dot{\Omega}$, one finds that the result can be presented as $\Omega_c = \Omega_{c0} + \dot{\Omega}\tau_F$, where Ω_{c0} is the true critical value and τ_F an effective flight time for the vortex loops to expand to rectilinear vortex lines and to be incorporated in the vortex cluster – in practice the time until the first rapid changes in the order-parameter texture and the NMR signal start to occur. It turns out that τ_F increases with decreasing temperature, owing to the rapidly decreasing mutual friction damping, from 10 s at $0.70\,T_c$ to 20 s at $0.52\,T_c$, when the AB interface is at an effective distance of 47 mm from the pick-up coil at the bottom of the sample cylinder. This agrees with the calculated estimate of τ_F, based on measurements of mutual-friction [5]. The main point in the present context is the fact that from one measurement to the next τ_F has a stable value in the crossover regime, *ie.* it does not fluctuate eg. by a factor of 2. This suggests that the nonlinear process occurs at an early stage of the expansion of the initial loops to rectilinear lines.

A measurement [6] of the AB-interface instability as a function of the current in the barrier magnet at constant temperature allows one to scan vortex formation at different rotation velocities. At $0.55\,T_c$ the range of Ω_{c0} is $0.9 \ldots 1.5$ rad/s. It is found that the probability for the nonlinear process to switch on increases with Ω_{c0}: below 1.1 rad/s no massive bursts were observed while above 1.4 rad/s every second vortex-formation event was followed by nonlinear vortex-loop expansion. This suggests that the probability of nonlinear loop expansion increases with the initial density of vortex loops in the instability event. In contrast, according to the KH theory [4] the initial loop number scales as $\Delta N \propto \Omega^{-1}$. It appears that it is thus the density rather than the number of vortices which controls the crossover to nonlinear loop expansion.

On the basis of these experimental considerations we can make two suggestions: 1) Nonlinear loop expansion takes place immediately after the initial vortex loops have been created in an instability event and the probability for the process to switch on increases with the density of the initial loops. This suggests that the process is controlled by inter-vortex interactions. 2) In the narrow crossover regime, where the nonlinear process starts to switch on with decreasing temperature, the quasiparticle mean free path is rapidly increasing. As a result, mutual friction drops and evolution times in loop expansion grow exponentially. Vortex motion acquires an increasingly larger azimuthal component and the expansion of the loops occurs slowly such that one end of the loop moves along a spiralling trajectory on the container wall, before the vortex spans the entire height of the rotating sample. The ratio of the azimuthal length of the trajectory to its height is determined by the ratio of the corresponding transverse and longitudinal mutual friction parameters. This ratio increases exponentially below $0.6\,T_c$ [5]. Thus loop expansion slows down below $0.6\,T_c$ and many vortices are simultaneously expanding along spiralling trajectories. This situation must play an important role in the crossover to turbulent loop expansion.

The new nonlinear mechanism of vortex proliferation changes drastically vortex formation below $0.6\,T_c$ when mutual-friction damping starts to decline exponentially. The new process resembles vortex-line avalanches in superconductors.

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