Vortex lines across the AB phase boundary in rotating superfluid ^{3}He

M. Krusius [a,1], A.P. Finne [a], R. Blaauwgeers [a,b], V.B. Eltsov [a,c], G.E. Volovik [d]

[a] *Low Temperature Laboratory, Helsinki University of Technology, P.O. 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*

Abstract

Vortex lines cannot end at the interface between the A and B phases of superfluid ^{3}He: They lie either parallel to the interface, coating it as a vortex layer, or cross it perpendicularly. In the A phase in a magnetic field there exists both a singly and a doubly quantized vortex structure. The latter forms first in most situations because of its lower critical velocity. The dominant interconnection of vortex lines across the AB boundary is formed by joining one doubly quantized A-phase vortex with two singly quantized B-phase vortices. The simpler topology of a direct connection between singly quantized vortices in both phases is found to exist, but only when the singly quantized A-phase vortex is already present and the AB interface is formed later.

Key words: superfluid ^{3}He; phase boundary; vortex structure; vortex formation; critical velocity; superfluid counterflow;

The single-quantum vortex (SQV) in the A phase is the energetically preferred structure which forms in *rotation cooling*, when the sample is cooled through T_c in rotation [1]. This vortex is rarely observed otherwise, since it has a higher critical velocity than the more frequently occurring double-quantum vortex (DQV). The latest rotating measurements have examined the stable vortex states at the phase boundary between the A and B phases. The presence of the AB interface might lead to situations (Fig. 1), which one could expect to favor the SQV in A phase.

The ^{3}He sample is contained in a long smooth-walled quartz cylinder which is closed off except for a small orifice at the bottom [2]. It provides the thermal connection to the heat exchanger on the refrigerator. A transverse AB phase boundary is stabilized with a magnetic barrier field H_b such that the sample is divided into cylindrical sections of A and B phases. This arrangement is stable and can be maintained while the rotation velocity Ω, temperature T, or magnetic field H_b are scanned. Thus different variations of measurements become possible to search for the presence of the SQV at the AB phase boundary:

1) *Increasing* Ω *sweep at constant* T, H_b*:* This is the basic variant, with the AB interface at a fixed location at all times. Vortex formation is examined as a function of the rotation velocity Ω. It is found that when the sample is slowly set into rotation, DQV lines are formed in the A-phase section in the same manner as if the AB interface were absent [3]. The low critical velocity [4] of the DQV is thus the selective feature here and no room remains for the SQV to be formed.

2) *Decreasing* T *sweep at constant* Ω, H_b*:* The second approach is to form SQV lines by cooling slowly ($\dot{T} \leq 20$ nK/s) at constant rotation ($\Omega \leq 1$ rad/s) from the normal to the A phase. The A-phase state, which is now formed, consists of a mixed vortex array with both SQV and DQV lines [5]. It is cooled further until the AB interface is formed within the barrier magnet. At low magnetic field (~ 10 mT) and high pressure (≥ 29 bar), the A→B transition supercools substantially. This is especially true of the first A→B transition after cooling from the normal phase and means that the phase front, when it is finally formed, moves at large

[1] E-mail: krusius@neuro.hut.fi

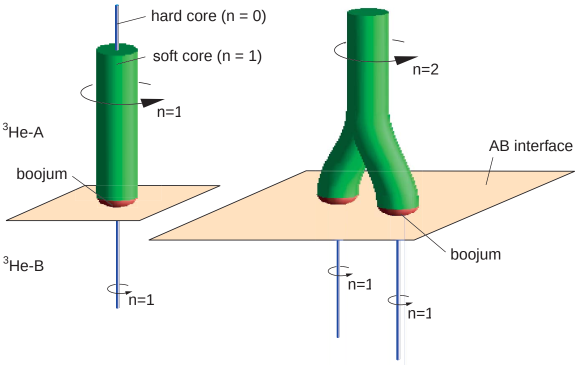

Fig. 1. Topology of vortex-line connections across the AB interface. *(Left)* Simplest configuration with singly quantized ($n=1$) vortices in both phases. These have "hard" non-singular vortex cores with a radius comparable to the superfluid coherence length $\xi \sim 10\,$nm. In A phase the hard core is embedded within a "soft" core of radius $\xi_D \sim 10\,\mu$m where only the orientation of the order parameter changes. The superfluid circulation around the A-phase SQV is produced by the soft core. The interconnection with SQV lines can be created by rotation cooling. *(Right)* The more tortuous configuration with the DQV ($n=2$) in the A phase. This vortex has only a continuous soft core. To connect to a single-quantum vortex in B phase, the two bound halves of the soft core have to move apart to match the inter-vortex distance in B phase, and two point singularities have to be created on the AB interface. This interconnection is created in a non-equilibrium process in the AB-interface instability [3].

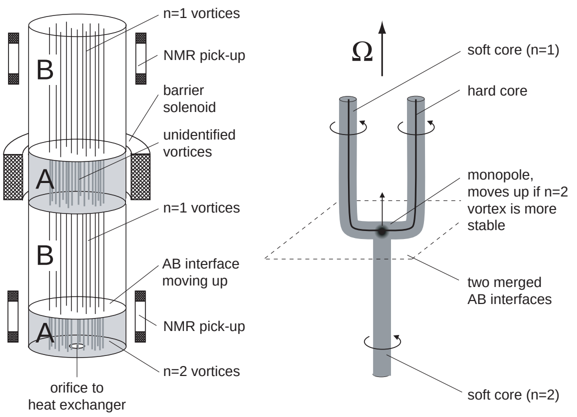

Fig. 2. B→A transition in a magnetic field at constant T and Ω. The initial state, except for a small seed of A phase, is B phase filled with the equilibrium number of SQV lines. (*Left*) Configuration of superfluid phases and their vortices when the sample is warmed, to analyze the type of vortex lines in the field-stabilized A phase. A second A phase region is emerging from the orifice on the bottom and rises to merge with the field-stabilized A phase in the center. (*Right*) Topology of the confluence of two SQV lines and one DQV line, when the two A-phase sections merge. The monopole is a hard-core point defect in the orbital $\hat{\ell}$ field. After formation it moves either up or down, depending on which vortex structure is energetically favored.

velocity out of thermal equilibrium, until it is stopped by the magnetic barrier. In this supercooled transition the AB front moves much faster than the vortex lines, which are slowed down by mutual-friction damping. Thus all the existing vorticity is incorporated into the newly formed B phase section of the sample [6]. We find that the division between SQV and DQV lines remains unchanged within the A phase section after such a transition. Thus we must conclude that both of the inter-vortex connections across the AB interface shown in Fig. 1 exist and are stable configurations. This is the first time that the interconnection across the AB interface has been stabilized in terms of SQV lines.

3) *Increasing* H_b *sweep at constant* Ω, T*:* The present measuring setup provides for the first time the possibility to investigate vortex lines at the AB interface in a magnetic B→A transition. This measurement makes use of our studies [7] of the shape of the AB interface at low values of the current I_b in the barrier solenoid. The measuring procedure is the following:

a) First the temperature is stabilized slightly below the A→B transition, where the entire sample would be in the B phase in the absence of a barrier field. b) Next I_b is swept down to a value where the A phase volume is reduced to a narrow ring-shaped sliver coating the wall of the container in the center of the barrier solenoid. c) Then the equilibrium vortex state is formed in the B phase at the chosen rotation velocity Ω, making use of the shear-flow instability at the AB interface [3]. Thereafter Ω is kept constant. d) The final operation is to sweep up slowly I_b. Since the A phase already exists in the toroidal sliver, there is almost no hysteresis in the magnetic field sweep.

During the field sweep the A phase sliver around the outer sample periphery starts to expand smoothly inward. The center region of the cylinder, which is B phase and filled with B-phase vortex lines, reduces in radius until finally it is closed up, two transverse singly-connected AB interfaces are formed, and a layer of A phase with increasing height starts to build up. At present we have no firm explanation what happens to the B-phase vortex lines, how they interact with the approaching AB interface, and whether they possibly lead to the formation of SQV lines in A phase, which would be the topologically least tortuous alternative.

In our experimental setup the final A phase state can only be analyzed by slowly warming the whole sample above the B→A transition so that the sections within the NMR pick-up coils are turned into A phase. Measurements of this state show that the A phase has almost the equilibrium number of DQV lines and that SQV lines are not detected. The straightforward conclusion is that the penetration of B-phase vortex lines through the AB interface is inhibited by a large energy barrier, which is similar to that for A-phase DQV lines at the AB interface [3]. Therefore in the magnetic B→A transition the A-phase vortices might form independently within the A-phase sliver [9] during the field sweep at their characteristic low critical velocity. In this case the final state includes only DQV lines. Their total number would correspond to that at the critical-velocity threshold, which is somewhat smaller than in the equilibrium state [6]. In this scenario the intermediate state with a dense B-phase vortex cluster inside a toroidal ring of A phase becomes a complicated arrangement where DQV lines with both signs of circulation are required to provide hydrodynamic stability.

The warm up of the whole sample to A phase is associated with an interesting complication: A new AB interface is formed during the warm up at the orifice and then starts to rise in the sample. It finally merges with one of the existing interfaces within the barrier solenoid (Fig. 2, left). Thus there remains the possibility that existing A-phase SQV lines have been replaced by DQV lines, when the AB interfaces merged during warm up. This depends on which one of the two structures is energetically favored. The ensuing situation is depicted in Fig. 2(right). At low velocities ($\Omega \lesssim 1\,\mathrm{rad/s}$) the SQV is the stable structure, at least at T_c [1], and thus one would expect to find some SQV lines. However, experimental inhomogeneities may intervene, which are known to favor the DQV [5].

These measurements suggest that the more straightforward topology of the A-phase SQV at the AB interface is not enough to enforce its formation. Large energy barriers prevent a smooth formation of vortex-line connections across the AB interface. The DQV with its lower critical velocity seems to restrict the counterflow velocities at all stages of the interconnection process to such low values that the SQV has no chance of forming.

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References

[1] Ü. Parts *et al.*, Phys. Rev. Lett. **75** (1995) 3320.

[2] R. Blaauwgeers *et al*, these proceedings.

[3] R. Blaauwgeers *et al*, preprint arXiv:cond-mat/0111343 and these proceedings.

[4] V.M. Ruutu *et al.*, Phys. Rev. Lett. **79** (1997) 5058.

[5] Ü. Parts *et al*, Phys. Rev. B **6**2 (2000) 5865.

[6] M. Krusius *et al.*, Physica B **197** (1994) 376; Phys. Rev. Lett. **71** (1993) 2951.

[7] V.B. Eltsov *et al*, these proceedings.

[8] Ü. Parts *et al.*, Europhys. Lett. **31** (1995) 449; J. Low Temp. Phys. **107** (1997) 93.

[9] E.V. Thuneberg *et al.*, Physica B **194-196** (1994) 779.