# Observation of a Remanent Vortex-Line Density in Superfluid Helium

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Sensitive ion-trapping measurements show that superfluid $^4$He at rest contains a substantial number of quantized vortex lines, metastably pinned between the walls of the container. This remanent line density appears to be history independent, and is established upon going through the lambda point.

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Some of the most interesting hydrodynamic problems in superfluid $^4$He involve the appearance and growth of quantized vortex lines. As a case in point, it is well known that a rotating bucket of superfluid becomes filled with a dense array of such lines, but it is a complete mystery where they come from. Similarly, the onset of turbulence in superflow is known to be associated with the sudden generation of a vortex-line tangle, yet a clear picture of how these singularities are initially generated is lacking. Most attempts at an explanation have concentrated on the quantum mechanical, thermal, or hydrodynamic nucleation of quantized vortices at the boundaries. Such attempts have not been notably convincing.[1] An alternative possibility,[2-4] which has occasionally been forwarded as a separate, "nonideal" mechanism pertaining to channel flow, is that pinned vortex lines can somehow initiate the growth of a vortex tangle. Historically, this suggestion has been entirely speculative, but recent work based on the idea of vortex-line reconnection[5] has shown that vortex singularities can multiply under the proper conditions. Although detailed calculations must still be performed, it now seems much more plausible that a sufficient number of originally pinned vortices could in fact generate a self-sustaining vortex tangle at sufficiently high flow velocities, or multiply to fill a rotating bucket with an array of vortices.

To make further progress it is crucial to establish whether such remanent vortex lines actually exist. Some evidence for this is provided by the early work of Vinen, which suggests that one or more vortices can become metastably attached to a fine wire. He concludes from this "...that isolated vortices are very likely to be present in apparently undisturbed helium... ."[6] To study this question further, we have performed an experiment which essentially consists of two parallel plates immersed in the superfluid. Our aim is to detect any quantized vortex lines which may extend between the two plates by making use of the fact that such a vortex will capture negative ions, i.e., electron bubbles, which must subsequently move along the line like beads on a wire.[7,8] Thus, the idea is to drift a negative ion current through the region between the plates, such that any vortices present will capture some of these ions and deliver them to one of the plates. This plate in turn functions as a collector attached to an electrometer. The relative ease with which very small currents can be measured, and the fact that signal averaging of the collected current can be implemented by switching the incident ion current on and off, make this a very sensitive measurement. More importantly, there exists the unique signature of a rather abrupt lifetime edge at $T \sim 1.7$ K, above which negative ions are not trapped on quantized vortices. By sweeping the temperature throught this region, one can discriminate against various leakage currents and unambiguously identify that part of the signal which arises from the presence of vortex lines.

In order to maximize the trapping rate, it is desirable to sweep a large current across the lines; hence, the applied electric field must have a substantial component parallel to the plates. In order to move the captured ions along the lines to the collector, however, it is also necessary to have a substantial field component perpendicular to the plates. In addition, it is important to minimize the amount of free-ion current leaking to the collector and to maximize the active volume where trapping can occur. These criteria, which cannot be satisfied in a conventional drift-cell arrangement, have led us to devise the geometry shown in Fig. 1. Ions are created behind the screen at $S$ by a radioactive source. Negative ions are pulled out of the source region, and follow the field lines as shown,[9] completely avoiding the collector. Any ion, however, which is captured by a vortex extending across the channel will be detoured to the collector as shown, always under the action of a strong field

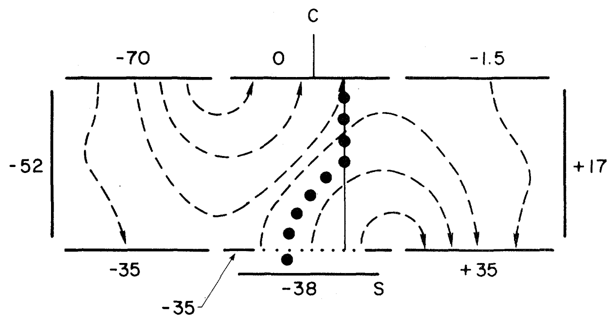


FIG. 1. Cross-sectional view of the cell geometry, showing typical biases. The distance between the top and bottom is 1 cm. The cell extends 6 cm into the plane of the figure. The collector sits in the middle of the top plate, and has an area of 2 $cm^2$. The negative field lines are shown as dashed lines. Dots show an ion trapped by a vortex pinned on the collector.

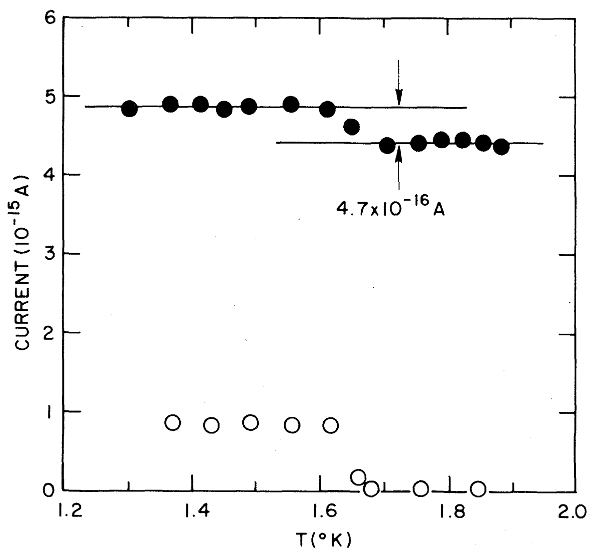


FIG. 2. Solid circles: current measured at $C$ in undisturbed helium. Open circles: 1/100 of the current observed at $C$ when the helium is turbulent, with $L = 9\times 10^3$ $cm^{-2}$.

along the line.

The current arriving at $C$ was measured by use of a Cary 401 electrometer with a 1-s response time. The noise in the unprocessed electrometer output was found to be about $2\times 10^{-15}$ A. This output was digitally signal averaged for 100 on-off cycles, and a digitally integrated 1.5-s interval from the off part of the resulting signal was subtracted from the corresponding on part. This procedure yielded an effective noise in the measured current of $5\times 10^{-17}$ A, the practical limit of the experiment.

The temperature-scanned current observed at the collector under these conditions is shown by the solid circles in Fig. 2. It is unambiguously clear that remanent vortex lines are present in this system. The size of the vortex-signal current step is found to be independent of the leakage current upon which it is superimposed. It is, however, affected by large changes in the injected current or in the field settings, as expected. By calibrating the measured signal against ion-trapping and transport measurements done in rotating buckets,[7,8] we estimate that there are ~ 15 lines/$cm^2$ pinned between the two plates. Because of the complicated field geometry, and the fact that we are extrapolating from rather poorly characterized data taken on dense vortex arrays to single vortices, this number should be considered as approximate only.

A rough theoretical upper limit for the remanent line density may be obtained as follows. If the lines are spaced a distance $\Delta$ apart, they will exert nonlocal velocity fields of order $\kappa/2\pi\Delta$ on each other, where $\kappa = h/m_4$ is the quantum of circulation. In equilibrium, each pinned vortex will take up a curved configuration such that the self-induced velocity $(\kappa/4\pi R)\ln(R/a_0)$ of the vortex line everywhere cancels the nonlocal field. Here, $R$ is the local radius of curvature, and $a_0 = 1.4\times 10^{-8}$ cm is the vortex-core radius. Hence, $\Delta \sim 2\langle R\rangle/\ln(\langle R\rangle/a_0)$, where $\langle R\rangle$ is the characteristic radius of curvature of the pinned vortices. Such a distortion, however, implies that the nonlocal interactions have caused the vortices to bow out by a distance of order $D^2/8\langle R\rangle$, where $D$ is the distance between the plates. It makes sense to require that the displacement of the vortices due to neighboring vortices not be larger than about half the interline spacing; otherwise, reconnection processes can cause further decay of the pinned vortices. Thus, $D^2/4\langle R\rangle < \Delta$. Eliminating $\langle R\rangle$, and setting the line-length density $L_R$ equal to $\Delta^{-2}$, one obtains the limit

$$L_R \lesssim 2\ln(D/a_0)/D^2. \quad (1)$$

This yields $L_R \sim 35$ lines/$cm^2$ for our geometry, in very good qualitative agreement with our observations. The reasoning leading to Eq. (1) further implies that $L_R$ scales in such a way that the number of lines stays approximately constant if the geometry is scaled to a different size. Only as $D$ approaches $a_0$ will the logarithmic term dominate and the remanent vorticity disappear.[10]

In fully developed superfluid turbulence it is

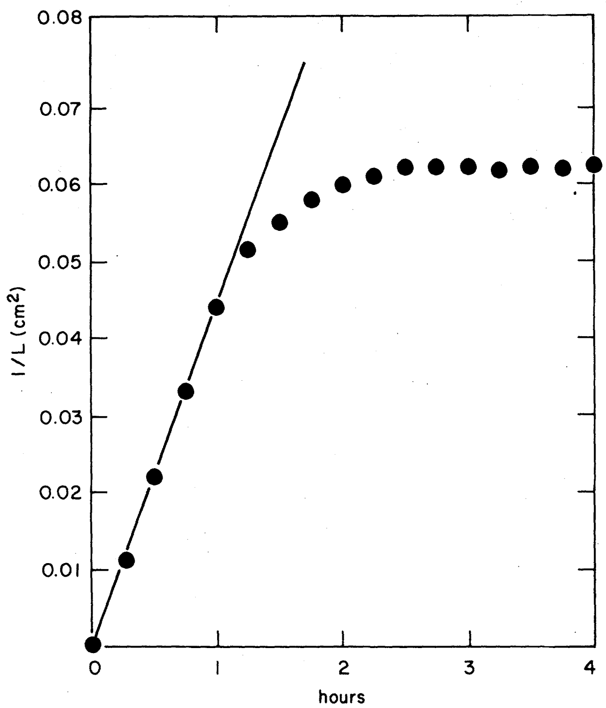


FIG. 3. Free decay from an initial line-length density $L = 9\times 10^3$ cm$^{-2}$ to the remanent density $L \simeq 15$ cm$^{-2}$ when the turbulence driver is turned off. The straight line corresponds to the behavior $\dot{L} = -\text{const} \times L^2$, as observed in Ref. 12.

easy to achieve a dimensionless line-length density $LD^2$ of $10^6$. As the driving velocity is reduced, this density drops rapidly until it reaches a critical value of order 10, at which point the vortex lines apparently disappear.[11] The fact that the critical line-length density is so close to the observed remanent density suggests very strongly that the vortices do not actually vanish, but are simply immobilized by pinning, at which point they are no longer observable by standard techniques.

The vortex-signal current in Fig. 2 is observed the first time the system is cooled below the lambda point, and is entirely repeatable with respect to rapid or slow thermal cycling above or below the lambda point. To study the effect of more drastic perturbations, ultrasound was used to generate vortex turbulence between the two plates. Figure 3 shows the collected current, translated into the effective line-length density, after the ultrasound is turned off. The vortex tangle decays from an initial density $L \sim 9\times 10^3$ cm$^{-2}$ to a final remanent density in a few hours, the initial decay behavior being in agreement with that reported in previous experiments.[12] The final value of $L$ is exactly the same as that obtained if the system is very carefully and slowly pumped through the lambda point. One may speculate that passing through the lambda point is equivalent to passing through a vortex-turbulent state, leaving the system with the maximum number of pinned vortices that can survive in metastable equilibrium.

By looking at the properties of the vortex-signal current when the system is turbulent, it is possible to compare the ion-trapping characteristics of the remanent vortices directly with those observed for the dense vortex tangle. The lifetime edge and the dependence of the signal current on the bias voltages were found to be the same for the two cases, further reinforcing the interpretation of our observations.

We conclude that any container of superfluid $^4$He, treated in conventional fashion, will be permeated *ab initio* by numerous quantized vortices stabilized by surface pinning. Thus the question of where quantized vortices come from appears to be answered—they are there to begin with. Whether there are special circumstances or experimental strategies which can produce a much lower level of remanent line density than we have observed is a matter requiring further exploration. In any case, it seems likely that most, if not all, experiments performed in the past on the growth of quantized vortex lines have started with a remanent vortex line density, and should be interpreted from that point of view.

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[1] We specifically exclude flow near the lambda point and thin-film phenomena from our considerations.

[2] R. P. Feynman, *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland, Amsterdam, 1957), Vol. 1, p. 17.

[3] W. F. Vinen, in *Liquid Helium*, edited by G. Careri (Academic, New York, 1963), Vol. 21, p. 336.

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[5] K. W. Schwarz, Phys. Rev. Lett. 49, 283 (1982), and Phys. Rev. Lett. 50, 364 (1983).

[6] W. F. Vinen, Proc. Roy. Soc. London, Ser. A260, 218 (1961).

[7] D. J. Tanner, Phys. Rev. 152, 121 (1966).

[8] W. I. Glaberson, J. Low Temp. Phys. 1, 289 (1969).

[9] The electrode geometry, desired voltage biases,

and the resulting field configurations were optimized by solving the two-dimensional Laplace equation with use of a finite-element scheme.

[10]One should also keep in mind the possible importance of thermal fluctuations as $D$ approaches microscopic scales. A similar consideration applies to the limit where the pinning sites become very small.

[11]This point of view is emphasized by J. T. Tough, *Progress in Low Temperature Physics*, edited by D. F. Brewer (North-Holland, Amsterdam, 1982), Vol. 8, p. 133.

[12]F. P. Milliken, K. W. Schwarz, and C. W. Smith, Phys. Rev. Lett. 48, 1204 (1982). The proportionality constant $\dot{L}/L^2$ is about 25% higher in the present experiment. This variation is within our estimated absolute accuracy for the determination of $L$.