# Trapping of persistent currents in superleaks*

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In a toroidal persistent-current apparatus which is partially packed with superleak, high-velocity persistent currents are found in the superleak and only barely perceptible currents, at most, are found outside the superleak.

Consider an annular cavity filled with superfluid helium. Persistent currents can be generated,[1] and if a typical dimension for the height or width is a fraction of a cm, the maximum current observed is about 1 mm/sec.[2] On the other hand, when the cavity is filled with a superleak consisting of a powder with a nominal grain size of 500 Å,[3] then persistent currents of $10^2$ cm/sec have been observed.[4] Suppose we now consider an annulus with cross section $0.5\times0.5$ cm$^2$ (the mean radius, $R=5.25$ cm) with only the bottom half, or so, filled with superleak of the grain size mentioned (as shown in Fig. 1). What can we expect in the two coexisting channels?[5] Will we have the same persistent current in the two channels and, if so, will they be about $10^{-1}$ cm/sec or about $10^2$ cm/sec? Or will they be small in the top part and large in the bottom? The experiment we report here was performed to answer this question and we can state that the last alternative is observed. Thus we have a high-velocity persistent current coexisting in close proximity with one of very low (or vanishing) velocity. The persistent currents in the powder are observed not to decay, and we thus assert that they are trapped, or caged, in the superleak. It is important to recognize that the angular momentum is constant despite the fact that there is a free exchange of superfluid mass across the boundary of the superleak.

It has been shown that two sound modes can propagate in the annular channel.[6] One is essentially a modified second-sound mode with a velocity $C_{II}$ given by

$$C_{II}^2=C_2^2\,\frac{\rho[L-(1-P)d]}{\rho(L-d)+\rho_s Pd}, \tag{1}$$

where $C_2$ is the velocity of second sound, $P$ is the porosity of the powder (the fraction of the volume of the superleak which is free), and $\rho$ and $\rho_s$ are the densities of He II and the superfluid component, respectively. Note that $C_{II}\geq C_2$.

The other mode is an interpolated first-fourth sound mode with a velocity $C_{14}$ given by

$$C_{14}^2=C_1^2C_4^2\,\frac{\rho(L-D)+\rho_s Pd}{C_4^2\rho(L-d)+C_1^2\rho_s Pd}, \tag{2}$$

where $C_1$ and $C_4$ are the velocities of first and fourth sound. Note that $C_1\geq C_{14}\geq C_4$.

Since both modes have components of first and second sound in the free region and fourth sound in the packed region, first-, second-, or fourth-sound transducers may be used to generate and detect both modes. We have used both first and second-sound condenser transducers in our experiments, with comparable results. We have experimentally verified that Eqs. (1) and (2) are correct to within about 2%.[7]

When there are persistent current velocities $v_f$ and $v_p$ in the free and packed parts of the channel, the Doppler-shifted velocities of these modes are[8]

$$C_{II}=(C_{II})_0\pm(\rho_n/\rho)\,v_f, \tag{3}$$

$$C_{14}=(C_{14})_0\pm\frac{\rho_s}{\rho}\,\frac{(L-d)v_f+P(2-P)dv_p}{L-d+P(2-P)d}, \tag{4}$$

where the zero subscript denotes the value in the absence of current and the plus and minus signs refer to propagation with and against the flow, respectively. $v_f$ is determined by measuring the splitting of the azimuthal $C_{II}$ modes and then $v_p$ by the splitting of the azimuthal $C_{14}$ modes.[9]

The situation is particularly simple when $v_p\gg v_f$ and $L-d$ is comparable with $d$, as in our experiments. Then

$$C_{II}=(C_{II})_0\pm(\rho_n/\rho)\,v_f, \tag{5}$$

$$C_{14}=(C_{14})_0\pm A(\rho_s/\rho)\,v_p, \tag{6}$$

where

$$A=\frac{P(2-P)d}{(L-d)+P(2-P)d}. \tag{7}$$

Persistent currents were generated by two different methods.

*Method* A. While rotating at constant speed the system is cooled through $T_\lambda$ and brought to rest at some low temperature. Measurements are made in the stationary state.

*Method* B. While stationary the system is cooled to some temperature below $T_\lambda$. It is then rotated and measurements are made while rotating.

The outstanding and striking result of rather extensive measurements was that the $C_{14}$ mode shows

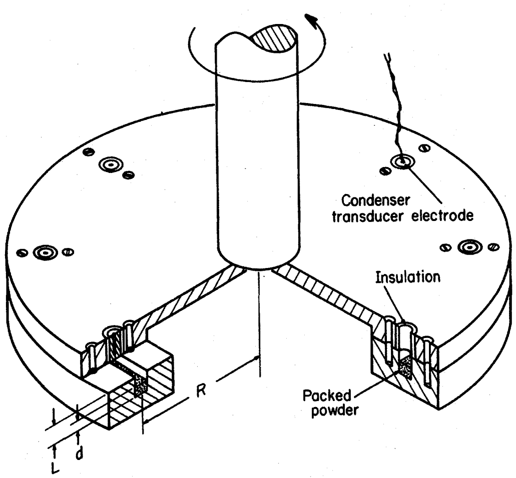


FIG. 1. Annular resonator for persistent-current measurements. The bottom of the resonator is packed to a depth $d$ with a powder of nominal grain size 500 Å. $L$ is 5 mm as is the width of the annulus. $R=5.25$ cm. The velocity of the persistent currents in the packed and free regions, $v_p$ and $v_f$, respectively, can be determined by measuring the splitting of $C_{II}$ and $C_{14}$ modes and using Eqs. (3) and (4), or (5) and (6).

considerable splitting and the $C_{II}$ mode showed no splitting at all, although peak broadening was observed. This broadening may be due either to a Doppler shift or the attenuation of second sound due to the presence of vortex lines.[10] Using method A at $T=2.10\,^\circ$K and rotation speeds which produce saturated critical velocities in the powder, the maximum broadening was observed with the maximum $d=4$ mm. If it was caused by a Doppler shift, then $v_f=1$ cm/sec. This we shall see is two orders of magnitude smaller than $v_p$. If part of the broadening was due to sound attenuation, the velocity is even less. Using method B, considerably greater broadening of the $C_{II}$ modes occurred. The vortex density in the free region is far greater with this method and sound attenuation must be the cause of the increased peak width.

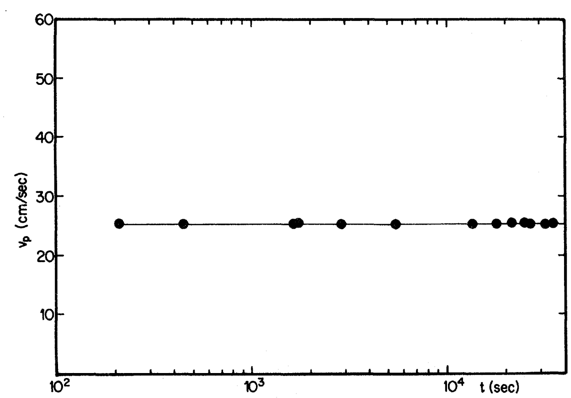


FIG. 2. Velocity of the persistent current in the packed powder $v_p$ as a function of time after its formation. The line is a least-squares fit to the experimental points. Within experimental accuracy there is no decay. The persistent current in the free region above the powder is 1 cm/sec or less. The saturated critical value of $v_p$ under the conditions of the experiment ($d=4$ mm, $T=1.3$ K) was 85 cm/sec.

TABLE I. Measured saturated critical velocities for various values of $d$ and their associated porosities. It is known that $v_{p\,\text{sat}}$ decreases as $P$ increases (Ref. 9), and it is possible that this accounts almost entirely for the difference in the values.

| $d$ (cm) | 0.1 | 0.2 | 0.3 | 0.4 |
|---|---|---|---|---|
| $v_{f\,\text{sat}}$ (cm/sec) | <1 | <1 | <1 | ≤1 |
| $v_{p\,\text{sat}}$ (cm/sec) | 68 | 75 | 76 | 85 |
| $P$ | 0.79 | 0.70→0.79 | 0.70→0.79 | 0.70 |

Detailed measurements of the splitting of $C_{14}$ modes were made with $d=4$ mm using method B at 1.4 °K. A vortex-free reversible Landau region is found to extend up to persistent current velocities of about 27 cm/sec. The saturated critical persistent-current velocity was found to be 85 cm/sec. Cycling the frequency at which the resonator is rotated yielded a hysteresis curve completely similar to those obtained in a fully packed resonator.[9] The $Q$'s of the measured $C_{14}$ mode were between 2000 and 4000 and the accuracy of determining the persistent current velocity is accordingly a fraction of 1 cm/sec.

Using method A at 1.3 °K, the decay of the persistent current was investigated with results shown in Fig. 2. The line drawn is a least-squares fit and within experimental uncertainty it is horizontal—there is no observable decay in 10 h. A saturated current had an observable decay which exceeded that observed in comparable fully packed cavities.[11]

The magnitude of the saturated critical velocity was examined as a function of $d$ using method A. Reduced values of $d$ were obtained by shaving down the cake of superleak in decrements of 1 mm and in the course of events we found that the porosity $P$ was greater at shallower depths. In Table I we list the saturated velocity, measured $10^3$ sec after forming the current. From previous measurements we know that the saturated velocity increases with decreasing porosity.[9] It is possible (in our opinion, probable) that the decrease in velocity with $d$ is due to the increasing porosity, so that $v_{\text{sat}}$ is independent of $d$ in the range of the experiment.

Figure 3 is a schematic drawing of the vortex-line configurations under conditions obtained in our experiments. For the purposes of illustration and discussion, the persistent current velocity in the top free region is taken to be zero.[12] Vortex lines terminate either on themselves or on the container and the latter condition is clearly energetically

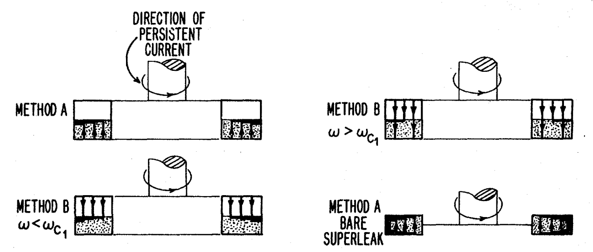


FIG. 3. Schematic of vortex-line configurations. The direction of the persistent current is indicated. The direction of rotation of the resonator (Fig. 1) is the same as that of the current in method A and opposite in method B. $\omega_{C_1}$ is the maximum velocity of rotation of the resonator for occurrence of the Landau state in the superleak.

favorable in the top left-hand figure. There is a sheath of vortex lines at the top surface and almost certainly in the superleak. The thickness of this sheath is measured in particle-grain diameters (which are large compared to the coherence length of helium) and is therefore small compared to $d$. The persistent current is confined to the superleak and the vortex line sheath can be considered necessary or responsible for this.

In the bottom left-hand figure the absence of persistent current in the top free part requires a vortex density that gives the solid body rotation of frequency $\omega$. Since the persistent current in the superleak is in the Landau state, there are no vortices in the superleak. Again there is a horizontal vortex-line sheath in the superleak at its top surface. When $\omega > \omega_{C_1}$ there are vortices in the superleak but with a density lower than that in the top region and the top surface.

In describing the coexistence of a large persistent current in the superleak with a vanishing one in the free region, there is a predilection to ascribe this to pinned vortex lines. From our discussion it is apparent that the really significant pinning occurs at the boundary rather than in the body of the superleak. After all, in the two left-hand figures in Fig. 3 the vertical vortex lines are in opposite parts of the apparatus, yet in both cases the persistent current resides entirely in the superleak.

The equilibrium thermodynamic state is one in which solid body rotation is approximated by the occurrence of the necessary density of vortex lines. Although this is always achieved in the free region and the required nucleation centers are present at the top surface of the superleak, the vortices do not extend down into the powder in the required density. This is possible because the pinnning is adequate for the presence of the horizontal sheath.

Our results clearly imply that persistent currents can exist in a superleak which is not in a container—a bare superleak—since the existence of the current hinges on the occurrence of a vortex-line sheath at the boundary of the superleak. The bottom right-hand schematic in Fig. 3 shows the vortex-line configuration in this case. Now vortices terminate on themselves. If large velocity-persistent currents occur in a bare superleak, this opens the possibility of increasing gyroscopic effects by the elimination of unnecessary mass. It, moreover, raises interesting questions about the nature of the pressure fields which are required to cage the currents within the vortex sheaths. We shall be looking into these matters.

Joseph Rudnick derived the results for the Doppler shift, Eqs. (3) and (4). We had numerous valuable conversations with Seth Putterman.

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[1]The velocity of the persistent current is the difference in the steady-state velocities of the normal and superfluid components.

[2]J. C. Weaver, Phys. Rev. A 6, 378 (1972). In careful experiments in our own laboratory using the Doppler shift of second sound we have never found evidence for a current exceeding this.

[3]Linde B 0.05-$\mu$m alumina polishing powder, Union Carbide Corp.

[4]J. S. Langer and J. D. Reppy, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland, Amsterdam, 1970), Vol. VI, Chap. I.

[5]In previous persistent-current experiments, unavoidably, there were small spaces unfilled with superleak, particularly when Vycor was used [J. D. Reppy (private communication)]. Thus there is circumstantial evidence for persistent currents in cavities incompletely filled with superleak.

[6]J. Rudnick, I. Rudnick, and R. Rosenbaum, J. Low Temp. Phys. 16, 417 (1974).

[7]Unpublished.

[8]Joseph Rudnick (private communication).

[9]H. Kojima, W. Veith, S. J. Putterman, E. Guyon, and I. Rudnick, Phys. Rev. Lett. 27, 714 (1971).

[10]H. E. Hall and W. F. Vinen, Proc. R. Soc. A 238, 204 (1956).

[11]H. Kojima, W. Veith, E. Guyon, and I. Rudnick, *Proceedings of the Thirteenth International Conference of Low Temperature Physics*, Boulder, 1972, edited by W. J. O'Sullivan, K. D. Timmerhaus, and E. F. Hammel (Plenum, New York, 1974), Vol. 1, p. 279.

[12]Whether $v_f$ is very small or identically zero is of no importance in the present context. If it is the former, from past experience we are sure it can be reduced to zero without significant change in $v_p$, by counter rotating the resonator with some small velocity and then returning it to rest again. In fact, one should be able to get $v_f$ and $v_p$ with opposite signs by this procedure.