

(1972).

¹¹C. B. Zarowin, IEEE J. Quantum Electron. **8**, 540 (1972).

¹²K. M. Kochelev and E. Ya. Kononov, in Proceedings of the Vavilov Conference on Non Linear Optics, Novosibirsk, U. S. S. R., 19-22 June 1973 (to be published).

¹³F. T. Arecchi, G. P. Banfi, and A. M. Malvezzi, Opt. Commun. **10**, 124 (1974).

¹⁴A. Carillon, Thèse d'Etat No. AO 8424, Université de Paris VI, Orsay, 1973 (unpublished).

¹⁵P. Jaeglé, A. Carillon, G. Jamelot, and A. Sureau, in Proceedings of the Vavilov Conference on Non Linear Optics, Novosibirsk, U. S. S. R., 19-22 June 1973 (to be published).

¹⁶A. Sureau, Ref. **6**, Vol. 1 p. 430.

¹⁷A. Carillon, G. Jamelot, A. Sureau, and P. Jaeglé, Phys. Lett. **38A**, 91 (1972).

¹⁸W. L. Bohn, Appl. Phys. Lett. **24**, 15 (1974).

¹⁹R. L. Kelly and L. J. Palumbo, U. S. Naval Research Laboratory Report No. 7599.

²⁰J. Söderquist, Nova Acta Regiae Soc. Sci. Upsal. **9**, 1 (1934).

²¹W. L. Wiese, W. Smith, and B. Miles, *Atomic Transition Probabilities*, U. S. National Bureau of Standards, National Standards Reference Data Series—22 (U. S. GPO, Washington, D. C., 1969), Vol. II.

²²A. Carillon, P. Jaeglé, and P. Dhez, Phys. Rev. Lett. **25**, 140 (1970).

Observation of Persistent Currents in a Saturated Superfluid Film*

Robert K. Galkiewicz and Robert B. Hallock†

Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01002

(Received 13 August 1974)

We report the first observation of a persistent flow around a closed path consisting entirely of saturated superfluid helium film in a macroscopic geometry in which the saturated vapor was in unconstrained proximity to the film.

We have observed a persistent current of saturated superfluid film in a configuration such that the *entire* flow path consisted of saturated film in intimate contact with the saturated helium vapor. This represents the first such observation under these conditions. It does not, however, represent *the* first observation of a persistent film current. Henkel, Kukich, and Reppy¹ have observed persistent currents in *unsaturated* films in porous material using the precise gyroscopic techniques developed by Reppy.² In those experiments a persistent current was formed by rotating the apparatus at temperatures above T_λ and then stopping the rotation slowly after cooling below T_λ .

In our own work we rediscovered the technique first used by van Alphen *et al.*³ in their observation of the persistent flow of bulk superfluid. The technique we shall describe here is also quite similar to one reported recently by Verbeek *et al.*⁴ except that our flow path contained no bulk fluid in a rouge plug and in our case the saturated vapor was in unconstrained proximity to the saturated film. Our studies were carried out from 1.16 K to 1.6 K. The basic measurement technique can be best described by reference to the schematic representation of the apparatus presented in Fig. 1. To produce a per-

sistent saturated-film current an oscillation is induced between our coaxial-capacitor level detectors A and B. During this oscillation the film flow takes place through path L since a small electric current is applied to heater S to block that path from film flow. When the velocity of film flow through L is large, the heater S is switched off and a persistent current is trapped

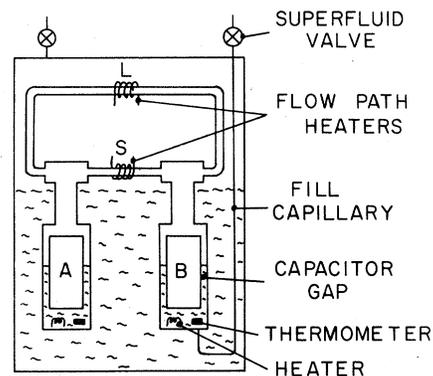


FIG. 1. Schematic representation of the persistent-current apparatus. The flow paths L and S lie in approximately the same horizontal plane but are shown vertically separated for clarity. The details of the capacitive reservoirs are given in Ref. 5. The entire detector assembly is housed in a sealed chamber which is immersed in the Dewar helium bath.

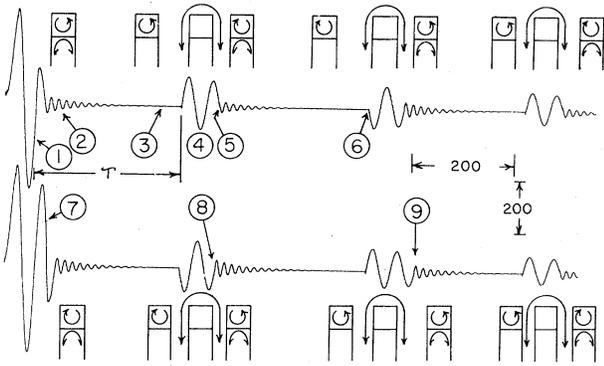


FIG. 2. Typical evidence for trapped saturated-film currents at 1.374 K. The data presented here are described in detail in the text. The schematic figures depict the sense of the saturated-film currents. For each trace the abscissa is time in seconds and the ordinate is the position in microns of the helium free surface in capacitor *A* relative to the equilibrium position.

in the loop. Some time later the heater *S* is turned on again and the kinetic energy contained in the persistent current is deposited in detector *A* or *B* depending on the sense of the persistent flow. As we shall show in Fig. 2 the persistent current can be trapped and released many times until eventually the initial trapped energy has been lost in the Atkins-Robinson^{6,7} oscillations between the two reservoirs. The existence of these persistent currents is in accord with the conclusions of Hallock and Flint⁵ that for temperatures below 2 K the damping observed in Atkins-oscillation experiments has little to do with dissipation processes which act *within* the film.

The actual apparatus consists of two coaxial-capacitor reservoirs⁸ of helium which are coupled to each other by means of two flow paths located 6 cm above the He II surface in the capacitors. The shorter path is 1.2 cm long and the longer is 36.8 cm. Each consists of a stainless-steel tube of inside diameter 0.137 cm. The tubes are joined to the coaxial capacitors by means of oxygen-free high-conductivity copper tees using indium-sealed flanges for each connection. Both stainless-steel tubes are in approximately the same horizontal plane. At the midpoint of each tube a coil of No. 45 Manganin wire is wound to provide the heater which acts to locally raise the superfluid film above T_λ to block the film flow path when that is desired. The wall thickness of the stainless steel at heater *S* is reduced from 0.020 in. to 0.010 in. to facilitate this

heating process. During normal operation both film flow tubes are *above* a superfluid bath which surrounds each capacitive detector. The bath and detector system can be filled separately through superfluid valves.⁹ Before a run the capacitors and film flow path are pumped to the 10^{-6} -Torr range for several days by an oil diffusion pump. At the midpoint of the pumping process the detectors and flow paths are flushed with clean¹⁰ helium gas.

We have initiated level oscillations through the long flow path *L* (with *S* blocked by the application of 1.3 mW) by applying heat to the heater in reservoir *A* or *B* and also by applying a dc voltage to the center conductor in reservoir *B*. These procedures work with equal success. Given such an oscillation it is a simple matter to trap a persistent current of either sense. All one need do is operate switch *S*. We refer to Fig. 2 which is very representative of our data.¹¹ In the upper trace we begin with an oscillation between *A* and *B* which takes place with film flow through path *L*. At position 1 the path *S* is opened and a persistent current is trapped in the flow loop. Atkins oscillations through path *S* take place as the helium levels in *A* and *B* reach equilibrium. The general character of the film flow in the apparatus is as sketched in the schematic figures. When the oscillations have settled we are left with the persistent current 3. After an arbitrary length of time τ the switch *S* is closed (by application of 1.3 mW) and the kinetic energy trapped in the persistent loop is transferred to level oscillations 4. We have waited up to $\tau = 10$ h between events 1 and 4 and are unable to observe differences in the amplitude of 4 for various τ . Thus, to within our present ability to measure a decay of the current, it appears to be *persistent*.

During oscillation 4 we select to trap a persistent current in the opposite sense and do so by opening path *S* at 5. Later at 6 the path *S* is again closed and we observe the characteristic transfer of energy from the persistent loop to the oscillations. The process may be repeated a number of times. The lower trace in Fig. 2 represents another sequence of persistent-current events initiated at 7 by the opening of path *S*. In this trace the initial trapped current was in a sense opposite to that in the upper trace. Note that at 9 a persistent current was returned to the loop in the same sense as it was stored at position 8.

It is also possible to remove nearly all the en-

ergy from the persistent state. This may be done by opening path S when the amplitude peak of the L -path oscillations is reached. The stored energy is subsequently lost through the Robinson^{5,7,12,13} dissipation process just as occurs on a smaller scale every time path S is opened (e.g., 2 and 5 in Fig. 2). This removal of the persistent current can be confirmed by closing S and observing that the subsequent level oscillations are of very low amplitude compared with those shown in Fig. 2.

After the initial trapping process the amplitudes that we observe after we sample for the presence of a persistent current indicate that our trapped velocity is the order of 5 cm/sec. This assumes a film thickness, δ , profile^{14,15} given by $\delta = 3.2 \times 10^{-6}/Z^{1/3}$ cm. Here Z is the height of the film path above the superfluid free surface in our detectors.

Our observations¹⁶ are in accord with the recent work of Verbeek *et al.*⁴ but important differences exist between the techniques. Here, the *complete* flow path consisted of a saturated film. No rouge plugs were present. This may be significant in that vortices trapped in microstructures are not available as an explanation of our results. In this sense our experiments are also different from those of Henkel, Kukich, and Reppy.¹ We are not convinced that vapor pressure is necessarily an important consideration, but in our case the path lengths were relatively short and open. Thus the helium gas was free¹⁷ to interact with the film and hence does not *appear* to hinder the stability of a persistent current.^{18,19} Why the work of Wang and Rudnick²⁰ and Wagner²¹ demonstrated that no persistent current could be produced in their experiments is not presently understood. A fundamental difference between this work and that of Ref. 4 on one hand and that of Wang and Rudnick²⁰ and Wagner²¹ on the other is found in the *mechanism* used to create the persistent-current state. We do not presently understand why rotational methods seem to fail when carried out in a *macroscopic* geometry.

We are indebted to L. J. Campbell for extensive discussions concerning the likely existence of persistent currents and for his encouragement and enthusiasm relative to our multiple-flow-path studies. We would like to thank E. B. Flint for assistance with some of the apparatus.

*Work supported by the National Science Foundation under Grant No. GH-34534A1.

†Alfred P. Sloan Research Fellow.

¹R. P. Henkel, G. Kukich, and J. D. Reppy, in *Proceedings of the Eleventh International Conference on Low Temperature Physics, St. Andrews, Scotland, 1968*, edited by J. F. Allen, D. M. Finlayson, and D. M. McCall (Univ. of St. Andrews Press, St. Andrews, Scotland, 1968), p. 178.

²J. D. Reppy, *Phys. Rev. Lett.* **14**, 733 (1965). See also J. R. Clow and J. D. Reppy, *Phys. Rev. Lett.* **16**, 887 (1966), and **19**, 291 (1967).

³W. M. van Alphen, R. de Bruyn Ouboter, K. W. Taconis, and E. von Spronsen, *Physica (Utrecht)* **39**, 109 (1968).

⁴H. J. Verbeek, E. von Spronsen, H. Mars, H. van Beelen, R. de Bruyn Ouboter, and K. W. Taconis, *Physica (Utrecht)* **73**, 621 (1974).

⁵R. B. Hallock and E. B. Flint, *Phys. Rev. Lett.* **31**, 1383 (1973), and *Phys. Rev. A* (to be published).

⁶K. R. Atkins, *Proc. Roy. Soc., Ser. A* **203**, 119 (1950).

⁷J. F. Robinson, *Phys. Rev.* **82**, 440 (1951).

⁸These detectors have been described in detail elsewhere; see Ref. 5.

⁹R. B. Hallock, *Rev. Sci. Instrum.* **43**, 1713 (1972).

¹⁰Helium gas used both for the flush and for the fill of the level-detector assembly is purified at 77 K by passing it through a Linde 13X molecular sieve and a Millipore filter located in the Dewar.

¹¹The traces we present here are typical. We have no noise problems. After waiting an apparently arbitrary time, upon closing S the trapped energy is precipitously dumped into level oscillations. These traces were obtained while very slowly removing helium through the capacitor fill capillary. This was necessary in order to keep the levels in detectors A and B constant. A very small superleak otherwise caused a very gradual increase in the volume of helium in the capacitors. By adding and removing helium through the fill capillary we have carefully checked that the persistent currents we observe have a behavior *independent* of a larger rate of change of helium volume (in *either* sense) than that caused by the small superleak. [Subsequent to the measurements reported here we repaired the small leak (which was in capacitor B) and repeated the experiment. Results identical to those presented in Fig. 2 were obtained at 1.37 K].

¹²J. F. Allen, J. G. M. Armitage, and B. L. Saunders, in *Proceedings of the Thirteenth International Conference on Low Temperature Physics, Boulder, Colorado, 1972*, edited by W. J. O'Sullivan, K. D. Timmerhaus, and E. F. Hammel (Plenum, New York, 1974), Vol. 1, p. 258.

¹³J. K. Hoffer, J. C. Fraser, E. F. Hammel, L. J. Campbell, W. E. Keller, and R. H. Sherman, in *Proceedings of the Thirteenth International Conference on Low Temperature Physics, Boulder, Colorado, 1972*, edited by W. J. O'Sullivan, K. D. Timmerhaus, and E. F. Hammel (Plenum, New York, 1974), Vol. 1, p. 253.

¹⁴E. B. Flint and R. B. Hallock, to be published.

¹⁵D. Hemming, *Can. J. Phys.* **49**, 2621 (1971).

¹⁶Earlier experiments in the presence of multiply con-

nected geometries caused by leaks [see E. F. Hammel, W. E. Keller, and R. H. Sherman, *Phys. Rev. Lett.* **24**, 712 (1970), as explained by L. J. Campbell, to be published; E. B. Flint and R. B. Hallock, to be published; E. B. Flint, Ph. D. thesis, University of Massachusetts, 1974 (unpublished)] have provided indirect evidence for the existence of persistent currents in saturated films.

¹⁷E. von Spronsen, H. J. Verbeek, R. de Bruyn Ouboter, K. W. Taconis, and H. van Beelan, *Phys. Lett.* **45A**, 49 (1973).

¹⁸G. A. Williams and R. Packard, *Phys. Rev. Lett.*

32, 587 (1974). See also Ref. 14.

¹⁹L. J. Campbell has pointed out that the gas-deposition mechanism suggested in Ref. 17 can be shown on thermodynamic grounds *not* to operate (private communication and to be published).

²⁰T. G. Wang and I. Rudnick, in *Proceedings of the Thirteenth International Conference on Low Temperature Physics, Boulder, Colorado, 1972*, edited by W. J. O'Sullivan, K. D. Timmerhaus, and E. F. Hammel (Plenum, New York, 1974).

²¹F. Wagner, *J. Low Temp. Phys.* **13**, 185 (1973).

Identification of Ion-Cyclotron Drift Instability with Discrete and Continuous Spectra*

H. W. Hendel† and M. Yamada

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540

(Received 24 June 1974)

Ion-cyclotron drift waves with discrete and continuous spectra are identified by measurements of ω and \vec{k} and explained by a theory which includes parallel electron current. This instability has a spectrum and effects on the plasma similar to those of ion sound, and can exist in plasmas which are ion-sound stable.

Drift or universal instabilities¹ play an important role in plasma confinement and heating: Their excitation mechanisms are often inherent to plasma production and confinement, and their effects may dominate plasma behavior. Low-frequency ($\omega \ll \Omega_{ci}$), ∇n -driven drift waves (DW) have been identified, described, and connected to plasma losses, in both the collisionless² and collisional³ regimes. However, ion-cyclotron drift waves (ICDW; $\omega \approx n\Omega_{ci}$), notwithstanding their theoretical analysis⁴ many years ago and despite their significance for both the heating of plasmas and the generation of anomalous plasma resistance, have not been identified conclusively,⁵ and observations of high-frequency ICDW ($\omega_{pi} > \omega \gg \Omega_{ci}$) with continuous, ion-sound-like spectra have not heretofore been reported.

The principal results of this work are the identification of discrete and continuous ICDW by measurements of ω and \vec{k} , and the explanation of these measurements in terms of a theory which includes parallel electron current ($k_z \neq 0$). Additional significance derives from the fact that a high-growth-rate instability with an ion-sound-like spectrum is destabilized in plasmas which are ion-sound stable ($T_e \lesssim T_i$). Moreover, the effects of ICDW on the plasma, ion heating, and anomalous resistivity are similar to those expected from ion sound. These latter results will be reported elsewhere.

The experiments were performed on the Princeton Q-1 thermally ionized potassium plasma,³ 128 cm long and 3 cm in diameter, with B in the range 1–7 kG. Collisions with neutrals are negligible. $T_e \lesssim T_i$, even in the presence of current, since the end plates act as electron-temperature sinks. Current is applied through the end plates parallel to B . Densities ($\lesssim 10^{11}$ cm⁻³) were measured with microwave cavity and radially movable Langmuir probes; electron temperatures ($T_{e0} = 0.25$ eV) and drift velocities u were determined with plane Langmuir probes which could be turned into and away from the current, thus permitting local measurements of u , v_e , n , and j simultaneously. Double probes with wire separations of 1–20 mm were used to measure wavelength. The axes of the double probes were aligned parallel to the plasma radius. The probes could be moved radially and rotated about their axes. By measuring the correlation between the signals from both wires as a function of the angle of rotation, wavelengths λ_y and λ_z could be measured with good accuracy. The experiments benefit from the low electron temperature, which allows us to raise u to $\sim \frac{1}{3}v_e$, for ~ 0.1 A, a small fraction of 1% of the end-plate emission. The plasma is electron rich, i.e., negatively charged, and electron-beam excitation of instabilities by the sheaths is thus not expected. In addition, Doppler shift due to $\vec{E} \times \vec{B}$ plasma rotation is neg-