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Probable Observation of the Two-Orifice Macroscopic Interference Effect in Superfluid Helium

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I have observed level differences between two baths of superfluid helium which are multiply connected by two orifices whenever the flow velocity past the orifices was of such value as to cause the quantum-mechanical phase difference between them to be an odd multiple of π.

Ever since the prediction of coherence effects in superconductors by Josephson[1] there has been a great deal of interest in observing similar phenomena in superfluid helium; however, to date none of these effects have been convincingly demonstrated.[2] This experiment is essentially the one proposed by Anderson[3] and is intended to be analogous to the experiment of Jaklevic *et al.*[4] who have observed quantum interference due to current flow in a superconductor joining two Josephson junctions. I observe a level difference between baths of superfluid helium which are multiply connected by two in-line orifices whenever the horizontal flow velocity is of such value as to cause the quantum-mechanical phase difference between the orifices to be an odd multiple of π.

The apparatus, shown in Fig. 1, consists of three reservoirs interconnected by a capillary with open ends at A and C and passing through B. The only openings to B are two laser-drilled holes as shown in the diagram. The reservoirs are completely enclosed except for the capillary and are immersed in a bath of pumped helium, normally held at about 1.4 K. The cryostat is shock mounted to prevent excessive vibrations. To produce the flow past the orifices I have installed two plungers, one in reservoir A and the other in C. Plunger P_A was used for most experiments while the primary purpose of P_C is to make final level adjustments, although it was also used to make several runs as will be discussed later.

Reservoirs A and B each contain a coaxial capacitor. Capacitor C_A is about 30 pF and C_B about 60 pF. Both are continuously monitored with capacitance bridges and lock-in amplifiers, and their values are displayed on a strip chart recorder. The experiment thus consists of monitoring the helium levels in A and B as the plunger is lowered or raised, thus imparting a known flow velocity in the capillary.

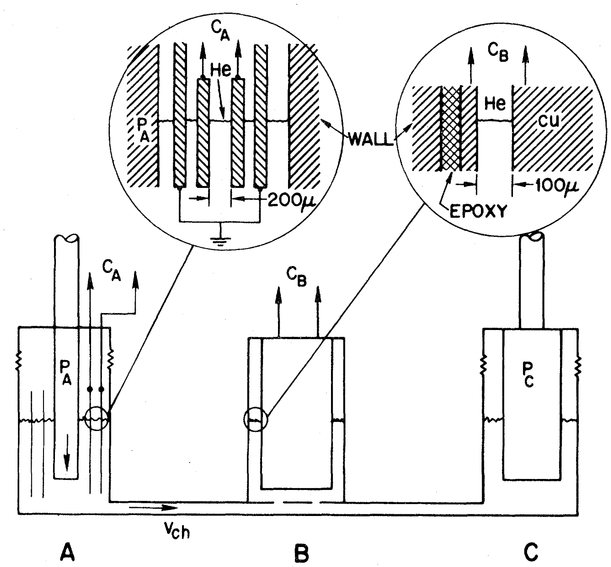


FIG. 1. Apparatus. Three in-line reservoirs are situated horizontally as shown. Their dimensions are 2.5 cm o.d. and 3.2 cm in height, excluding the bellows in A and C. The capillary is 813 μm o.d., 100 μm wall. The orifices are ≈ 10 μm at the narrowest point. C_A is made from four thin-wall tubes; the inner and outer ones shield the capacitor. In B the annular space between the two sides of C_B is the only space available for the liquid to enter. P_A is 0.635 cm o.d. and has a 0.25-cm travel distance. P_C was 2.032 cm o.d. for some runs and 1.854 cm o.d. for others. Both plungers can be driven mechanically by a variable-speed motor.

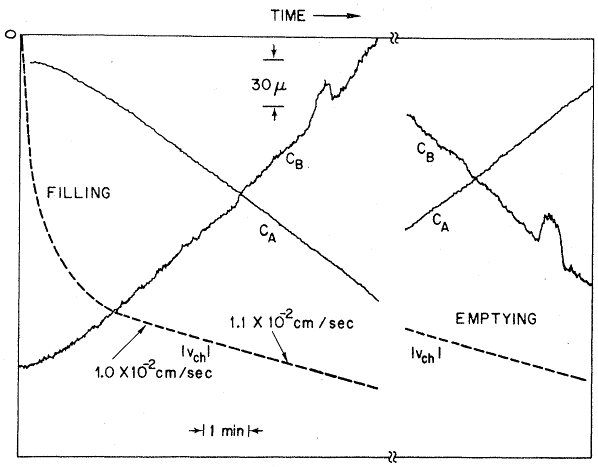


FIG. 2. Typical signal traces: Starting on the left the two solid traces show the behavior of C_A and C_B as P_A is being driven. The channel velocity is shown by the dotted line.

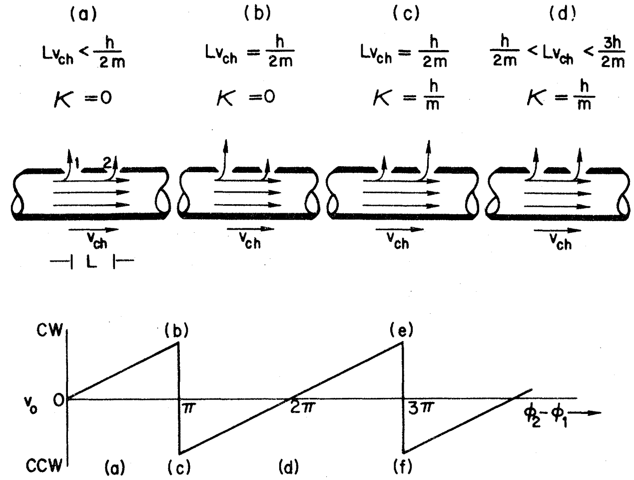


FIG. 3. Schematic representation of flow patterns near the orifices at different flow velocities in the channel for the case when the reservoirs are being filled.

I show in Fig. 2 some typical traces obtained with plunger P_A and with spacing between orifices equal to 500 μm. The voltages corresponding to levels in A and B are purposely of opposite sign so they can be summed to eliminate the parabolic base line. The dotted line represents the flow velocity in the capillary calculated from the plunger velocity and spacial geometry. Note that the curves for C_A and C_B look rather similar except that C_B shows a departure from C_A at about $(1.1 \pm 0.1)\times 10^{-2}$ cm sec. In filling and emptying, the level in B rises with respect to A and then drops to the same level. Similar signals were also seen at flow velocities 3 and 5 times that value. Subsequently, the orifices were changed to a new spacing and it was noted that the value of the velocity when a level change could first be seen was inversely proportional to the spacing. The signal could also be seen at the same velocity when P_C was used instead of P_A.

In trying to explain these results it is tempting to pursue the analogy with superconductors as was done by Anderson[5]; however, as we shall see later there are several puzzling inconsistencies which suggest that other effects must be taken into account to explain all the observed features. With this in mind, let us then follow the analogy with superconductors. If we take the definition that a liquid is a superfluid if the particle field operator Ψ has a macroscopic mean value of

$$\langle \Psi(\vec{r},t)\rangle = f(\vec{r},t)\exp\{i\Phi(\vec{r},t)\}, \tag{1}$$

then it readily follows that the superfluid velocity is

$$\vec{v}_s = (\kappa_0/2\pi)\nabla\Phi, \tag{2}$$

where $\kappa_0 = (h/m) = 10^{-3}$ $\mathrm{cm^2/sec}$ or one quantum of circulation. If we consider our geometry we see, as shown in Fig. 3, that the phase difference between points 2 and 1 is

$$\Phi_2 - \Phi_1 = [(2\pi L)/\kappa_0]v_{\mathrm{ch}}, \tag{3}$$

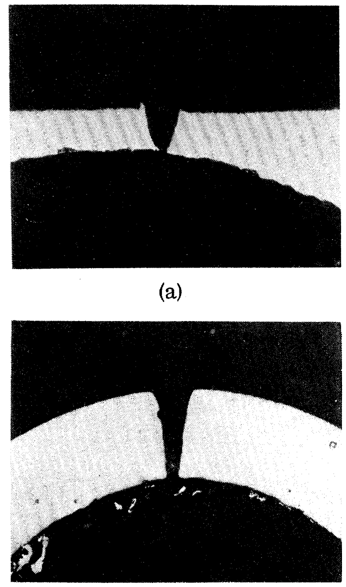
where L is the distance between the two holes.[6]

When the fluid is at rest, $\Delta\Phi = \Phi_2 - \Phi_1 = 0$ and the circulation κ measured on the path enclosing the two openings is also zero ($\kappa \equiv \oint \vec{v}\cdot d\vec{l}$). As v_{ch} is increased $\Delta\Phi$ increases, but the circulation must remain at zero or make a quantum jump which means that there will be an imposed circulating screening current going through the openings. The direction of this current v_0 will be clockwise if the geometry is as shown. Superimposed on v_0 will be, of course, an additional velocity which is due to the reservoir filling or emptying. The total velocity is roughly indicated by the length of the arrows. As we increase v_{ch} up to the point when $\Delta\Phi = \pi$, then there must be π phase difference through the holes and across the top[7]; however, rather than increasing v_0 further it becomes energetically favorable for it to change from clockwise to counter-clockwise motion and cause the phase difference through the holes and on top to go from π to $-\pi$. This can easily be accomplished by blowing out a vortex ring from an orifice or moving a vortex line across it. In any event this abrupt change in circulation from 0 to (h/m) changes the flow pattern. Another vortex changes the circulation back to zero, and it is feasible that near $\Delta\Phi = \pi$, we might have an instability where the circulation will be flipping back and forth as the vortices keep popping out.[8] Vortex emission, of course, creates a pressure head[9] which is the observed signal. Using Eq. (2) we get v_{ch} to be equal to 1.0×10^{-2} cm/sec for a π phase difference which is in very good agreement with data shown in Fig. 2.

Increasing the velocity past this point should permit the circulation to stabilize at (h/m), since $|v_0|$ is decreasing, until it again becomes energetically favorable for κ to make a quantum jump which would occur at $\Delta\Phi \doteq 3\pi$, etc. This is schematically sketched in Fig. 3. This process will continue until some critical flow velocity is reached.

In total, seven different geometries were used, five sets of double orifices (three 300-μm, a 500-μm, and a 750-μm spacing), a single orifice, and an open line to B from A and C reservoirs. In the latter two cases no signal was ever observed. Of the remaining, one of the 300-μm and the 500-μm spacings showed reproducible signals of high quality as shown in the figures. The 750-μm run was somewhat marginal and two of the 300-μm runs were poor, insomuch that when observed, the signals were small and often appeared randomly. After a series of runs were finished with one spacing, the orifices were dissected and photographed and it was concluded that the best series were obtained with orifices shaped as shown in Fig. 4(a) and the poor runs were with those shown in Fig. 4(b).[10] Generally speaking we also found the signals improved by working with low helium levels in the reservoirs. Furthermore, quite often instead of just showing a constant level difference there were fluctuations in the level. Finally, some signals appeared to be inverted, i.e., the level in B was lower than in A, but none of these was as large and clear cut as the ones shown in Fig. 2. Furthermore, the majority of the inverted signals occurred with the poorer orifices.

In closing let me mention a few of the obvious puzzles that remain. First, the fact that the signal is mostly in one direction, namely the level in B is higher than in A, is puzzling since in the superconducting interferometer the signal changes sign when the flow direction in the orifice is reversed. Quite possibly the reason for the unidirectionality might be the orifice geometry. Secondly, the signals occur at subcritical velocities. This might be explained, however, on the basis that rather than generating new vortices the pressure head occurs because of existing vortices being pushed around or trapped in the orifices. This idea is supported by the fact that cooling rapidly through T_λ thus generating a greater amount of turbulence yields the best results.[11] Finally it should be mentioned that unlike the case for superconductors, it is very difficult to make real "weak" links in He^4 because of the very small coherence length.



(a)

(b)

FIG. 4. (a) Cross section of a portion of a capillary containing an orifice that produced good signals. The light area is the stainless-steel capillary wall. The opening is about 8 μm at the bottom and 40 μm near the top. The wall thickness was machined to about 40 μm. (b) An orifice 13 μm at the bottom and 50 μm on top with wall thickness equal to 100 μm. This orifice produced poor results.

I wish to thank P. W. Anderson for encouragement throughout this experiment and would also like to thank him, T. A. Fulton, and C. M. Varma for many helpful conversations. I would also like to thank H. W. Dail for his endless patience in collecting the data.

[1]B. D. Josephson, Phys. Lett. 1, 251 (1962).
[2]See D. L. Musinski and D. H. Douglass, Phys. Rev. Lett. 29, 1541 (1972), and references therein.
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A sketch of the proposed experiment is shown there in Fig. 9.

[4]R. C. Jaklevic, J. Lambe, J. E. Mercereau, and A. H. Silver, Phys. Rev. 140, A1628 (1965). The analogous experiment is the one in which they produced phase modulation by motion of superconducting electrons. On a base film they located two weak-link junctions which were connected electrically in parallel but separated 8 mm apart. By passing a drift current through the base, they observed a periodic maximum Josephson current through the junctions. Our channel velocity v_{ch} and filling rate in B are analogous to their drift current and maximum Josephson current, respectively.

[5]An alternative to the quantum mechanical explanation is to assume *a priori* that circulation is quantized and then pursue classical fluid dynamics.

[6]Using similar phase-coupling arguments, H. E. Corke and A. F. Hildebrandt, Phys. Rev. A 2, 1492 (1970), explained observed restrictions in the flow of helium.

[7]The phase difference is largest in the neighborhood of the narrowest point in the orifice. From Fig. 4(a) we see that the opening is actually located at the bottom of a deep blind hole. Thus the wall thickness around the narrow opening is only a few microns thick.

[8]To date we have been unsuccessful in detecting the vortices individually but further tests are planned.

[9]See, for example, Ref. 3 or W. Zimmerman, Jr., Phys. Rev. Lett. 14, 976 (1965). Experimentally this was observed by R. Carey, B. S. Chandresekhar, and A. J. Dahm, Phys. Rev. Lett. 31, 873 (1973).

[10]The phase drop, $\Delta\Phi$, in the orifice needs to be $\lesssim \pi$, but since $\Delta\Phi = \int_0^L v(x)\,dx$, where L is the thickness, we need to minimize the thickness of the narrowest area which is done in the orifice shown in Fig. 4(a) but not in Fig. 4(b).

[11]The effect was not observed above T_λ.

Hydrodynamics of ^{3}He in Anisotropic A Phase

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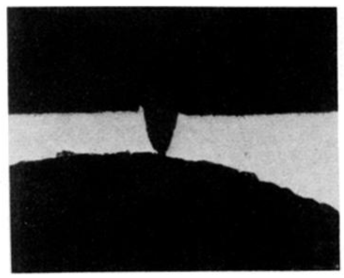
The hydrodynamic theory of mass transport in A-^{3}He is derived from that phase's broken symmetries and thermodynamics. First, second, and fourth sound as well as orbit waves are obtained as the normal modes.

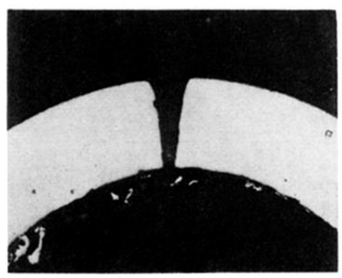
From the very active experimental[1] and theoretical[2,3] work on the low-temperature phases of ^{3}He it has become clear that several symmetries are simultaneously broken in the so-called A phase. One of these, broken gauge invariance, is common to all known superfluids. In addition, orbital rotational invariance is also broken in A-^{3}He, because of an alignment of the orbital angular momentum of the triplet pairs.[4] Since this implies a directional long-range order in real space (rather than spin space like, e.g., in ferromagnets), one is strongly reminded of the order in a nematic liquid crystal.[5] However, unlike in nematics, the directional order parameter in A-^{3}He (being a certain angular momentum) is ***odd*** under time reversal and transforms like an *axial* vector under spatial inversion. In this latter respect A-^{3}He is more similar to ferromagnets.[6]

These facts have far-reaching consequences for the low-frequency collective excitations in the A phase. Clearly, low-frequency "orbit waves" must exist, which are the Goldstone excitations of the broken rotational symmetry.[7] Even more exciting, the new order parameter, being a vector in real space and odd under time reversal, can couple to the mass current, as pointed out by de Gennes.[8]

A rich literature on this subject has already grown up.[9] The results obtained have been restricted in their domain of validity, however, since they were based on gradient expansions of the Ginzburg-Landau type and/or on BCS weak-coupling theory, eventually corrected for Fermi-liquid and spin-fluctuation effects. By contrast, the present paper is concerned with the general hydrodynamics of A-^{3}He, which has not been given previously. This theory has the advantage of being model independent and rigorous in the hydrodynamic limit. The obvious disadvantage is the impossibility to compute the phenomenological parameters entering the hydrodynamical equations within the same approach. In the case of superfluid ^{4}He the corresponding theory is the well-known two-fluid hydrodynamics[10] which has proven to be of great value. For simplicity we will disregard spin motion and consider linearized hydrodynamics only.



(a)



(b)

FIG. 4. (a) Cross section of a portion of a capillary containing an orifice that produced good signals. The light area is the stainless-steel capillary wall. The opening is about 8 μm at the bottom and 40 μm near the top. The wall thickness was machined to about 40 μm. (b) An orifice 13 μm at the bottom and 50 μm on top with wall thickness equal to 100 μm. This orifice produced poor results.