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Experiments on quantized circulation in superfluid ^{3}He

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This paper provides a brief description of recent experiments measuring the fluid circulation in ^{3}He. In the B phase, the circulation around a 16 μm diameter wire is found to be quantized in units of $h/2m_3$. Possible future experiments are also described.

It is widely believed that quantized circulation is a fundamental property of any superfluid system [1]. The fluid circulation must be quantized in units of h/nm, where m is the mass of the individual atoms in the fluid and n is an integer that depends on the microscopic process responsible for the macroscopic quantum state. For the case of ^{4}He, the interacting atoms experience a Bose condensation into the superfluid state and $n = 1$. This fact has been demonstrated in several different types of experiments [1].

In ^{3}He there are two superfluid states [2], A and B. The macroscopic quantum states are a consequence of Cooper pairing of ^{3}He atoms. Consequently, it is expected that the quantum of circulation should exhibit $n = 2$. This paper is a brief summary of an experiment [3] in the B phase which directly demonstrates that the circulation is quantized [4] and that the quantum unit is $h/2m_3$.

The techniques used to directly determine the circulation constant in ^{4}He are not all applicable to the case of ^{3}He. Charged vortex rings have not yet been detected in ^{3}He and, due to the difficult ultralow temperature technology, individual quantized vortices have not yet been identified. However, experiments now in progress in Helsinki may soon change this latter statement [5].

We have pursued the technique developed by Vinen [6] for ^{4}He, namely, measuring the circulation around a stretched vibrating wire. The basic idea is that the presence of circulation around a vibrating wire causes the plane of vibration to precess at a rate proportional to the circulation.

There are two difficult aspects of using this technique in ^{3}He. The first problem is that the normal component viscosity of ^{3}He is very great. This viscosity will normally damp the vibration of a small wire before any appreciable precession has occurred. However, at low enough temperatures, the viscosity decreases rapidly [7] and for $T/T_c < 0.2$, the experiment is feasible.

The second obstacle is the need for a rotating refrigerator capable of achieving the required low temperatures. The ability to rotate the experiment is the most obvious way to create circulation around the wire. A description of our rotating facility is given in ref. [8].

In the actual experiment a superconducting wire (16 μm diameter and 5 cm length) is stretched along the axis of a cylindrical housing. A magnetic field of 50 mT is oriented perpendicular to the wire. If the wire vibrates in the field a detectable emf is produced across the wire's ends. As the wire precesses with respect to the field, the detected voltage exhibits a characteristic modulation, whose beat frequency tells the circulation.

Thus far we have performed experiments only on the B phase because that is the phase that exists normally at very low T/T_c. We have concentrated on measuring states of trapped circulation. The creation of such a metastable state is accomplished by first rotating the cryostat at

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some angular velocity Ω, to create the circulation, and then stopping the cryostat. The dynamics of how the circulation, presumably in the form of a quantized vortex, becomes attached to the wire, is unknown. However there is evidently a sufficient energy barrier so that the circulation, once attached to the wire, persists, even if the cryostate remains at rest for many hours. This is perhaps the most elemental demonstration of a persistent current.

Some details of our experiment are presented in ref. [3]. Figure 1 is the fundamental result of the experiments thus far. The horizontal axis shows the rotation rate of the cryostat before the measurement was performed. It is clear that the circulation is indeed quantized and that the quantum unit is $h/2m_3$. It is also evident that there is a characteristic angular velocity below which no circulation becomes trapped.

The remainder of this paper describes some of the topics which can possibly be investigated using this vibrating wire technique.

Perhaps the most obvious experiment is to measure the circulation in the A phase. Here the expected results are less clear than in ^{3}He-B. For A phase superfluid in a simply connected domain, the circulation is not necessarily quantized. Furthermore, in a simply connected circular cylinder, there should be a circulation about the central axis even in the absence of any rotation. This latter phenomenon is a consequence of the l vector texture expected for this geometry and gives rise to an intrinsic angular momentum for this particular system [2].

The presence of the wire, along the cylinder's axis, should create a radially direct l texture which will be characterized by circulation quantized in units of $h/2m_3$. However it is not obvious if this simple texture will exist in the presence of inevitable stray heat currents. The experiment must be performed in the presence of a 0.6 T magnet field, needed to stabilize the A phase at $T/T_c < 0.2$.

Assuming that quantized circulation is observed in the A phase several intriguing questions arise. If the circulation is first trapped in the B phase, will it survive when the slow application of a magnetic field eventually transforms the B to A? One can ask the same question about the inverse transformation from A to B. The dynamics of this phase transition in the presence of circulation involves the details of the

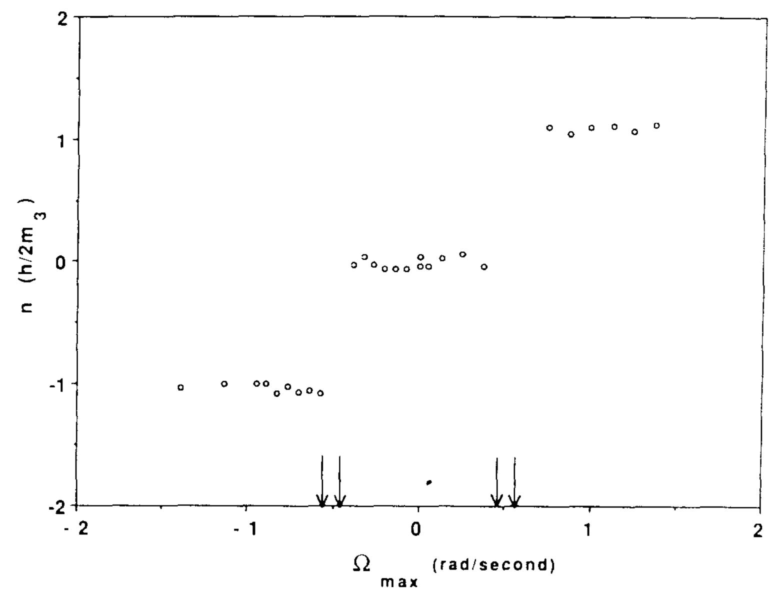

Fig. 1. The measured value of the trapped circulation as a function of the maximum rotation speed, Ω_{max}. In the region between the sets of arrows the circulation is unstable.

physics of the A–B interface in the presence of quantized circulation.

Possibly related to this last question, is the prediction [9] of monopole-like structures at the A–B interface, in the presence of a quantized vortex line. Such a singularity may give rise to excess dissipation in the wire or may even change the precession rate. However, the presence of the wire in this problem may erase the singular nature of this feature.

It will also be interesting to observe the effect of a trapped circulation quantum on the critical velocity for creation of quasiparticles. Experiments in Lancaster have demonstrated that at very low temperatures a vibrating wire exhibits a very well defined critical velocity, above which the wire's motion breaks Cooper pairs [10]. The presence of circulation near the surface of our 16 μm diameter wire should shift this wires critical velocity by about 6%. This shift will be another measure of the quantum of circulation.

It is clear that the positive results of the quantized circulation experiments in ^{3}He-B have opened up a considerable number of questions that should be accessible to experimental answers. In the next few years we expect to see a considerable expansion of our knowledge of this very interesting physical system.

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References

[1] D.R. Tilley and J. Tilley, Superfluidity and Superconductivity, 2nd edition (Adam Hilger, Bristol, 1986).
[2] D. Vollhardt and P. Wolfle, The Superfluid Phases of Helium 3 (Taylor & Francis, London, 1990).
[3] J.C. Davis, J.D. Close, R. Zieve and R.E. Packard, Phys. Rev. Lett. 66 (1991) 329.
[4] There have been many experiments performed, in Helsinki, on quantized vortex lines in ^{3}He. A recent review of this work is given in: P. Hakonen et al., Physica B 160 (1989) 1.
[5] J. Pekola et al., Physica B 178 (1992) 238 (these Proceedings).
[6] W.F. Vinen, Proc. R. Soc. London A 260 (1961) 218.
[7] A.M. Guenault, V. Keith, C.J. Kennedy, S.G. Mussett and G.R. Pickett, J. Low Temp. Phys. 62 (1986) 511.
[8] J. Close, R. Zieve, J.C. Davis and R.E. Packard, Physica B 165 & 166 (1990) 57.
[9] M.M. Salomaa, Czech. J. Phys. 40 (1990) 761.
M.M. Salomaa, Nature 326 (1987) 367.
[10] C.A.M. Castelijns et al., Phys. Rev. Lett. 56 (1986) 69.