Experiments on the vortex dynamics in superfluid ^4He with no normal component

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We report results from ongoing experiments on the dynamics of quantized vortices in superfluid ^4He at temperatures below 0.2 K. Charged vortex rings of micron size were used to detect the presence of vortices, to create a turbulent tangle, and to charge an array of rectilinear vortex lines. The results reveal that the ion technique has great potential for the study of vortices in ^4He at very low temperatures.

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1. INTRODUCTION

Recently, attention was attracted to the problem of turbulence in superfluid helium at very low temperatures where there is no normal component left at all ^{1,2}. It is believed that in this limit the dynamics of turbulence may be different and more tractable than in viscous classical liquids or in superfluids described by two-fluid hydrodynamics. Trapping of negative ions on the cores of quantized vortices in superfluid ^4He is arguably the most promising technique for vortex detection when $T \ll 1$ K. In this paper we will briefly outline the various types of ion experiments with vortices in ^4He already in progress at Manchester.

The details of the experimental cell and its use for preliminary experiments with steady-state currents are described elsewhere ^{3,4}. It consists of six square electrodes (plates) making a cube-shaped experimental space with sides of length 4.5 cm. The ions can be injected through gridded openings in the center of either the “left” or “bottom” plates and current can be detected by electrometers connected to any of the plates. The “right”

and “top” plates have Frisch grids to facilitate detection of ion pulses. The cryostat was rotated around its vertical axis at angular velocities Ω between 0.075 and 3 rad/s thus producing vortex arrays of density $L = 2\Omega/\kappa$ between 1.5×10^3 and 6×10^4 cm⁻². The majority of experiments reported here were performed using isotopically pure ⁴He at $T = 0.14$ K and $P = 0$ with the ions being injected from the left and pulled by a horizontal electric field to the right collector. As discussed in Section 3, the final stage of collecting surviving charge required pulling the ions by a vertical field to the top collector.

An electron injected into liquid helium self-localizes in a spherical cavity of radius of ~ 20 Å⁵. At $T < 1$ K and not very high pressures most ions quickly nucleate vortex rings on which they get trapped⁶ producing a stable “charged vortex ring” complex. The dynamics of charged vortex rings in an electric field are described elsewhere³.

The ion technique for detecting vortices works as follows. Ions are injected into liquid helium and pulled through it by an applied electric field. If vortices are present, some ions will be trapped and then restricted to move along the vortices. The associated decrease and deflection of the ion current will tell us about the density of vortex lines and their motion.

The charged rings have a very large (of the order of their diameter⁷) capture diameter for charge transfer onto existing vortex lines. In our experiments with short pulses of ions such charged rings have a very well-defined drift time of $\approx 0.4 - 1$ s for electric fields $E_h = 0 - 20$ V/cm, and hence well-defined radii ($R \sim 1 - 2$ μm) and energies. This suggests that they are produced near the emitting tip, i.e., before entering the main region of the experimental cell.

2. TURBULENCE FROM INJECTED CHARGED RINGS

Let us consider relaxed non-rotating helium with the horizontal electric field E_h around 20 V/cm. As mentioned above, at low enough charge densities, the pulses of charged rings arrive at the collector after a well-defined time, see Fig. 1. However, if the duration of the injected pulse is increased above 1 s, a long tail of decaying current appears after the main pulse has arrived at the collector. We also observed the suppression of the amplitude of arriving pulses when the pulse repetition frequency is too high; only for pulses separated by at least 50 s is there no suppression. This was even the case for the shortest pulses of duration 0.1 s indicating that some density of slowly moving charged vortex rings, or maybe a slowly decaying vortex tangle, is left after the passage of a sufficiently large number of charged rings.

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Fig. 1. Ion pulses of different duration ($\Omega = 0$). The pulse repetition frequency was 0.02 Hz.

The slowly moving rings (or tangle) then impede newly arriving pulses of charged rings. We can speculate that some initial rings no longer propagate independently but apparently collide, reconnect and get entangled on the way, similar to observations with beams of uncharged rings in ^4He ⁸ and ^3He - B^9 . The results should then look more like a distribution of charged rings of various sizes.

The current tails are observed either at $\Omega = 0$ or at moderate angular velocities of rotation $\Omega < 1$ rad/s. However, at sufficiently high $\Omega (> 1$ rad/s) the tails disappear completely even though a sharp pulse of charged vortex rings still arrives at the collector with the same time of flight. This indicates that the dense array of rectilinear vortices stops very large charged vortex rings and opposes the development of the turbulent tangle.

3. DIFFUSION OF TRAPPED CHARGE AT STEADY ROTATION

The dynamics of vortices can be investigated by watching how an equilibrium vortex array at steady rotation behaves when charged. The only way for an electron trapped on a vortex line to move is to either follow the moving vortex line or slide along it. In this experiment, we prepared a certain density of charge in the cell while preventing electrons from leaving in the

Fig. 2. Surviving trapped charge versus time for different horizontal fields.

vertical direction (i.e. along the vortex lines) by applying suitable negative stopping potentials at the top and bottom. Then we waited for a given time τ during which there was no injection of new ions and the existing charge was acted upon by an electric field E_h perpendicular to the vortex lines. After time τ had elapsed, a vertical field, parallel to vortex lines, was turned on and all surviving charge from the central region of the cell, Q , was collected by the collector at the top plate. Figure 2 shows the dependence of Q on τ for various strengths of the horizontal field E_h .

Without the external horizontal pulling force, the trapped charge initially decays (presumably due to the Coulomb repulsion of its space charge) but then reaches a nearly steady value of around $Q = 0.1$ pC. However, with a strong pulling force provided by $E_h = 40$ V/cm, the charge decays as $\tau^{-\alpha}$, where $\alpha \approx 1.2$ as shown by the dotted line in Fig. 2. In intermediate fields, between 0 and 40 V/cm, the charge decays before reaching a steady value which decreases with increasing E_h . In the high field regime where $Q \propto \tau^{-\alpha}$, the diffusion time is found to be proportional to Ω . This is actually quite natural for quasi-2d transport where the mean free path for charge transfer is restricted by rectilinear vortices whose density is proportional to Ω . The relevant mechanisms of charge transfer might be reconnections of rectilinear vortex lines and/or emission of ballistic vortex rings.

The transients of the surviving charges arriving at the collector after turning the vertical (collecting) field on were also analyzed. They revealed

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Fig. 3. Transients during the collection of the surviving charge. The arrows roughly indicate two distinct arrival times.

that there are two distinct arrival times: the first one shorter than 0.1 s and the second around 0.2 s (see Fig. 3). The former can be associated with the trapped ions sliding along the vortex lines which is a very fast process that should take about 1 ms. The latter may be caused by trapped ions producing very small charged vortex rings (or kinks on vortex lines) upon switching the electric field. These small rings would indeed take about 0.2 s to travel a distance of ~ 2 cm in vertical field $E_v \sim 20$ V/cm, which were the conditions of the experiment. However, for smaller values of E_v we would expect faster arrival (because the rings would gain less energy from the electric field and hence would have a smaller radius) which apparently disagrees with Fig. 3. More experiments are required to gain an understanding of this phenomenon.

4. SPIN-UP AND SPIN-DOWN

The dynamics of vortex motion and multiplication upon quickly starting and stopping rotation were probed by observing changes in the magnitude of the ion current perpendicular to the axis of rotation. Both the DC current (see Fig. 4) and pulse techniques gave similar results. At temperatures below 0.5 K, the time needed for the ion current to relax after changing Ω was of order 500 s. This indicates the time required for the superfluid to dissipate the kinetic energy of the macroscopic flow in order to approach the equilibrium state of either solid body rotation or rest.

Fig. 4. The absolute value of the DC ion current in a 20 V/cm field during starting and stopping rotation. The shaded areas indicate uniform acceleration ($t = 0 - 75$ s) and deceleration ($t = 1200 - 1275$ s).

5. CONCLUSION

We have succeeded in creating and investigating vortices in superfluid ^4He at $T < 0.2$ K using negative ions. Further experiments are under way. We thank Henry Hall, Joe Vinen, Peter McClintock, Steve May, Lev Levitin and Sio Lon Chan for their involvement. The research is supported by EPSRC through grant GR/R94855.

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