Vortex metastability to perturbative counterflow in superfluid ^{4}He

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Superfluid provides a unique environment in which to study vortex dynamics. Although experiments in superfluid face difficult practical challenges, the quantum vortices found in superfluid are simpler to understand theoretically than their classical counterparts. We present an apparent threshold for vortex depinning as well as evidence that temperature oscillations dislodge pinned vortices via counterflow.

I. INTRODUCTION

A. Vortices

It is both important and difficult to understand vortices in practical, everyday contexts. Vortices—regions of fluid rotating about an axis line—lie at the heart of many systems with applications in aerodynamics, meteorology, helioseismology, and many others. Experimental study of classical vortices faces challenges that result from the many available degrees of freedom. Vortex lines may move and curve, and in classical vortices the velocity field around a given axis line may change as a function of time: for example, as a tornado dissipates energy, the velocity field may slow down. Also, classical vortices need not have continuous lines.

Fortunately, we can experimentally study many fundamental vortex properties and phenomena in quantum vortices, with the advantage of the elimination of these aforementioned nuisance phenomena. In contrast to their classical counterparts, however, experimentally producing quantized vortices proves more difficult; quantized vortices do not occur in gas or liquid but rather in superconductors and superfluid.

B. Helium and Superfluid

Superfluid can be thought of as, in some ways, analogous to superconductors. At sufficiently cold temperatures, helium behaves as a superfluid. Due to the weakness of attractive inter-atomic forces between helium atoms, the two stable isotopes of helium have the lowest boiling points of all the elements—3.2 K for helium-3 and 4.2 K for helium-4. The weakness of the interactions comes from the fact that helium, a noble gas, is chemically inert; there is a supplementary effect in that the energy of localization of each atom decreases with increasing average inter-atomic distance. Its low boiling point makes helium uniquely useful in cryogenic experiments. In particular, when cooled to 2.17 K and below, helium-4 exhibits a transition from its normal liquid state, known as He-I, to He-II, a superfluid [1]. Helium-3 also exhibits superfluidity, although it transitions at a far colder temperature. Our experiment deals exclusively with superfluidity in helium-4; unless otherwise noted, further discussion of helium implies helium-4.

Superfluidity cannot be adequately explained by classical physics. As bosons, many helium-4 atoms can simultaneously exist in the same state (helium-3 atoms, as fermions, cannot!). This can only occur at low temperatures where the low thermal energy permits condensation of many atoms into the same state. The superfluid transition point in helium-4, called the lambda point, occurs at $T_\lambda = 2.17$ K [1].

One very successful model of superfluidity, known as the two-fluid model, states that a superfluid essentially acts as a mixture of a normal fluid component and a superfluid component. The ratios of the densities—ρ_s/ρ and ρ_n/ρ, where ρ_s and ρ_n are the densities of the superfluid and normal fluid densities, respectively, and with $\rho_s + \rho_n = \rho$ the total fluid density—depend directly on temperature [1]. Whereas the normal component retains the properties of normal liquid helium, the superfluid component has no viscosity, has quantized circulation, excellent thermal conductivity, vortex lines that must extend to boundaries or form loops, and other unusual properties. The vanishment of viscosity in the superfluid, again, bears analogy to vanishment of electrical resistance in a superconductor; current flow of superfluid experiences no energy dissipation. This, and quantization of circulation, are what make superfluid simpler to study than classical fluid.

Quantization follows from the fact that the superfluid state is described by a single macroscopic wavefunction with coherent phase [2]. Taking m_4 as the mass of the helium atom, the superfluid velocity relates to the phase of the wavefunction by:

$$\vec{v} = \frac{\hbar}{m_4}\vec{\nabla}\phi. \tag{1}$$

Immediately we see that the superfluid flow must be irrotational:

$$\vec{\omega} \equiv \vec{\nabla} \times \vec{v} = \frac{\hbar}{m_4}\left(\vec{\nabla} \times \vec{\nabla}\phi\right) = 0. \tag{2}$$

We call $\vec{\omega}$ the vorticity, and it is zero everywhere in the superfluid. Excluding the trivial case of no superfluid

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rotation, $\vec{\omega}$ must not vanish everywhere; the vorticity has non-zero value in the vortex core. Evidently, the vortex core does not consist of superfluid. Circulation is defined as the line integral over a closed loop l of the velocity field:

$$\kappa = \oint_l \vec{v} \cdot d\vec{l}. \tag{3}$$

This relates to the vorticity:

$$\kappa = \iint_S \left(\vec{\nabla} \times \vec{v}\right) \cdot d\vec{S} = \iint_S \vec{\omega} \cdot d\vec{S}. \tag{4}$$

S represents a surface whose boundary is the loop l. The vorticity only has a non-zero value in the vortex core, so the circulation vanishes if and only if l is simply-connected within the superfluid; the circulation depends only on the enclosed vortex lines.

The condition of a single-valued wavefunction imposes a periodic boundary condition on ϕ, in turn placing a condition on the circulation:

$$\kappa = \frac{\hbar}{m_4} \oint_l \left(\vec{\nabla}\phi\right) \cdot d\vec{l}. \tag{5}$$

The boundary condition on ϕ dictates that going through one period around the loop must change the phase by $2\pi n$ where n is an integer. This, in combination with eq. (5), yields the result [1]:

$$\kappa = \frac{hn}{m_4} \qquad n = 0, \pm 1, \pm 2, \ldots. \tag{6}$$

Further, two circular loops of different radii around the same vortex must have the same circulation, so the velocity field around a single infinitely-long vortex line falls off as $v \propto 1/r$, since the circumference of the loop relates proportionally to its radius r. In more realistic situations such as finitely-long vortex lines (attached to container boundaries) and more complicated situations, this dependence is often still a good approximation.

Vortices carry energy and angular momentum. The kinetic energy relates to that of the circulating fluid; it depends on the circulation, the size of the container, and the radius of the vortex core. Due to energy optimization, the radius of the vortex core in helium-4 measures approximately 1.3 Å in diameter.

II. EXPERIMENTAL SETUP

A. Refrigerator

The experiment occurs in a small cylindrical cell attached to the bottom of a refrigeration system [1]. Around the cell, two perpendicularly oriented superconducting magnets can together provide a magnetic field in any arbitrary horizontal direction through the cell. The refrigerator uses two stages of evaporative cooling, one with helium-4 and one with helium-3, to cool the cell to a temperature around 300 mK. A vacuum can encloses the refrigerator and cell system to insulate them. The whole experiment then, with some manipulation, fits through the neck of a dewar (vacuum-insulated container) of liquid helium such that the outside of the vacuum can is directly immersed in liquid helium. The walls of the vacuum can quickly cool to the temperature of the liquid helium in the dewar (4.2 K). We put a small amount of gaseous helium into the vacuum can to serve as an exchange gas: this provides a small thermal link between the fridge and the vacuum can itself. Conduction through the exchange gas brings the fridge down to 4.2 K as well; without this it would take a long time, since vacuum insulates very well.

Once the fridge has cooled, the exchange gas must be removed; in order to achieve temperatures much colder than that of liquid helium, there cannot be a thermal link between the experiment and the vacuum can. A sorb serves to collect the helium exchange gas, such that the vacuum can is re-evacuated. The sorb, made of activated charcoal (powdered charcoal processed to have extremely high surface area), serves to adsorb the helium exchange gas once the sorb cools close to helium's boiling point. Gases tend to stick to surfaces in proportion to the available surface area when the temperature of the surface gets near or below the boiling point of the gas; the enormous surface area of the sorb tends to capture the exchange gas as the system cools to 4.2 K.

The first stage of the fridge works to cool from 4.2 K down to approximately 1.7 K through evaporative cooling. A small pipe extends from the fridge outside the vacuum can. This line sits in the liquid helium in the dewar and leads into the vacuum can, where it snakes through several components, including a relatively large plate of metal (the 1 K plate). The tube connects to a pump which reduces the pressure in the line, which reduces the vapor pressure of the liquid helium at the open end of the line. Since this preferentially allows hotter atoms to escape the liquid, the average temperature of the liquid falls. This process, called evaporative cooling, reduces the temperature of the first stage of the fridge to about 1.7 K.

A closed system of gaseous helium-3, in contact with the 1 K plate, cools to about 1.7 K. Helium-3 boils at 3.2 K: some of the helium-3 condenses into liquid and drips into the helium-3 pot. Another sorb, this one located inside the helium-3 chamber, effectively pumps on the gas to reduce the vapor pressure above the liquid helium-3. This second stage of the refrigerator can cool the helium-3 down to 300 mK; the experiment cell, in contact with the pot, now cools to its final temperature. We use a sorb on the helium-3, rather than an external pump as with the first stage, because helium-3 is extremely scarce and the cost is prohibitively expensive. Thus we keep it in an entirely closed system so as not to lose any.

As the sorb pumps on the helium-3, eventually it captures nearly all of the helium-3 in the system: the second-

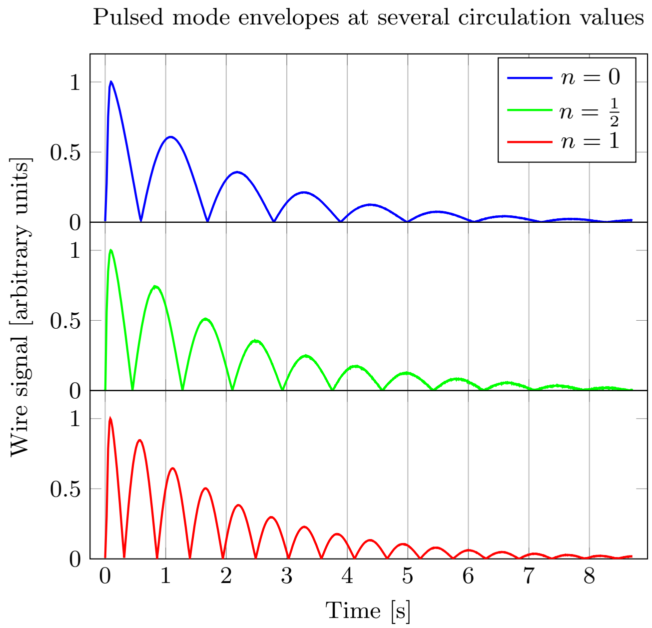

FIG. 1. Actual signal envelopes of the voltage induced across the vibrating wire. Wire had (a) no vortex pinned along its length, (b) vortex pinned along half its length, (c) vortex pinned along its entire length. The relative angle between the velocity and the magnetic field cycles as the wire vibration processes. Minima correspond to vibration parallel to the magnetic field. The measured data match the fit (9) extremely well.

stage evaporative cooling halts, the fridge warms, and it cannot function until a restart. The fridge restart consists of the use of a resistive heater to apply heat to the sorb—the effectiveness of the sorb drops when its temperature exceeds the boiling point of helium—such that it releases most of the captured helium-3. After several minutes, the heater stops, at which point the evaporative cooling begins again. The fridge, by itself, could run continuously for well over a day between restarts. With the experiment present and hooked up, and the fact that the helium in-fill line necessarily thermally links components at different temperatures, the fridge can usually only run for around four hours at a time between restarts.

B. Vibrating Wire

The experimental cell, filled with helium-4, has a thin, taut, superconducting wire that spans the cell vertically. At 300 mK, the helium in the cell behaves as a superfluid. We can excite a vortex in the superfluid through rotation of the entire fridge: the various wires and tubes disconnect except for the siphon line pump, and we manually rotate the system several times. Then we stop rotation, reconnect the wires, and make measurements. If we have exicted a vortex, sometimes it will bounce around in the cell and simply decay. Other times, it will land on the thin wire, because it is energetically favorable for the vortex to have the wire act as its core [1]. Since the diameter of the wire ($\sim 17\mu$m) far exceeds the diameter of the free vortex core, the wire essentially shields the superfluid from the largest velocities present very near the vortex axis from the $1/r$ dependence. Thus the total kinetic energy of the vortex decreases by pinning along the wire.

The horizontal magnetic field through the cell allows us to vibrate the thin wire: a pulse of current sent across the wire feels a deflection due to the Lorentz force. Due to imperfections in the wire, and more importantly the rotational motion of the fluid around the vortex, the wire has two resonant frequencies that correspond to two modes of vibration. With a vortex pinned on the wire, the modes essentially represent clockwise and counterclockwise elliptical motion. When plucked, both modes of the wire are excited and beats in the motion of the wire occur at a frequency equal to the different between the two resonant frequencies.

In a slightly simpler but still useful picture, the wire vibrates in a plane. As the wire vibrates through the rotating fluid of the vortex, the Bernoulli force deflects the wire in a direction perpendicular to its motion. This effects a precession of the vibration plane.

The wire can be partially covered by the vortex [1]. As described in section III, we can measure the fraction of wire covered by the vortex. This fraction generally, but not always, corresponds to a vortex that begins at the bottom or top of the wire and goes along the wire for that fraction of the length, then detaches from the wire. Past this attachment point the free vortex stretches through the cell, with the end on the boundary of the cell. The end on the cell wall can move and generally moves in the direction of the fluid rotation around the vortex. Since the wire is slightly off-center in the cell, as the free vortex precesses around the cell its length changes; to conserve energy the length of the pinned vortex (and so the location of the attachment point) changes, and thus the amount of the wire covered by vortex changes in a quasi-periodic fashion [1].

III. EXPERIMENTAL METHODS

A. Pulsed Mode

We measure the fraction of the wire covered by the vortex. The wire has two resonant modes and the presence of the vortex along the wire causes the frequencies of these modes to separate; the magnitude of the difference in frequencies depends on the fraction of the wire covered by vortex.

A short current pulse (~ 1 ms) across the wire deflects the wire by the Lorentz force (due to the magnetic field in the cell). Then, due to tension, the wire vibrates at a frequency close to 540 Hz. Thanks to the inviscidity of the superfluid component of the helium, only the normal

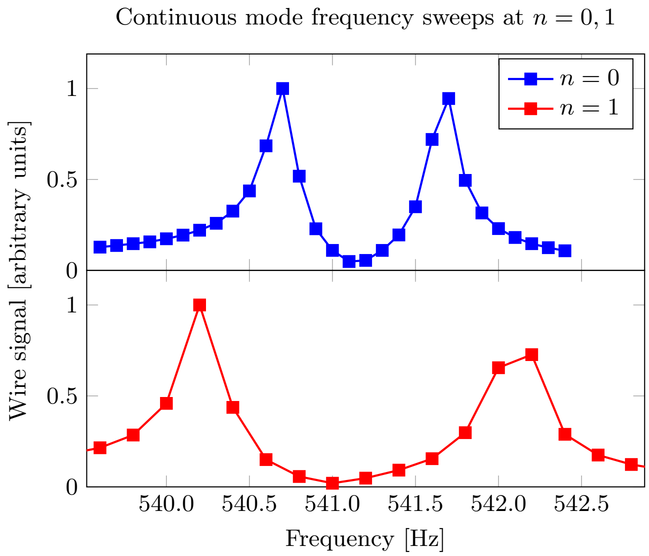

FIG. 2. Wire response to sinusoidal drive current at several frequencies. Each point shows the average response amplitude measured over one minute. Wire had (a) no vortex pinned along its length and (b) vortex pinned along its entire length. The separation of resonant frequencies $\Delta\omega$ changes based on the circulation on the wire. In (a), $\Delta\omega \sim 1.9$ Hz while in (b), $\Delta\omega \sim 1.0$ Hz. Note that the value of the center of the double-Lorentzian profile does not depend on the circulation.

fluid component contributes any damping force on the wire—thus the wire vibrates for a long time. The minor damping from the normal fluid component causes the average wire velocity to decay exponentially, with a time constant close to two seconds. We can generally extract useful information for about ten seconds after a current pulse, but this decay duration depends on the amplitude of the pulse. Note that several hundred vibration periods occur over the course of a decay.

As the wire decays, we measured the induced voltage across the wire; this depends on the velocity of the wire and its direction relative to the magnetic field. The plane of vibration of the wire rotates due to the Bernoulli force in the rotating fluid at a rate determined by the fraction of wire covered by the vortex. The relative angle between velocity and magnetic field cycles. Denoting the average of the resonant frequencies of the wire as ω_0, the magnitude of the wire's velocity has the form:

$$\vec{v}\,(t) = Ae^{-t/\tau}\sin\left(\omega_0 t + \phi_0\right) \tag{7}$$

Now we denote the small separation of frequencies between the two modes as $\Delta\omega$. Due to the periodic cycle of the relative angle between wire motion and field, the induced voltage behaves as:

$$\varepsilon\,(t) = Ae^{-t/\tau}\sin\left(\omega_0 t + \phi_0\right)\left|\cos\left(\left(\Delta\omega\right)t + \phi\right)\right| \tag{8}$$

We align the magnetic field direction to cause equal excitation of both vibration modes. Beats in the signal

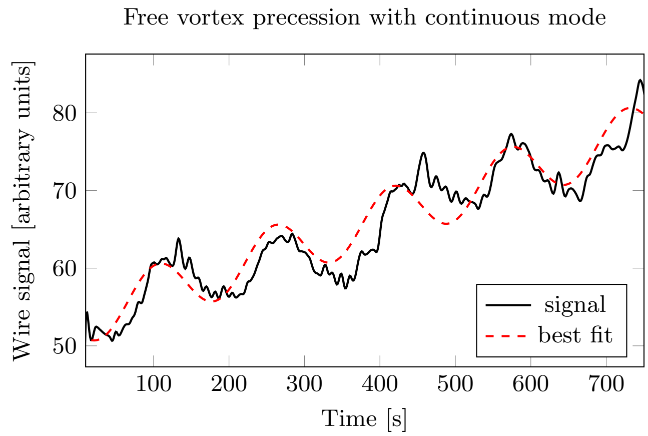

FIG. 3. An apparent precession phenomenon measured at 541.9 Hz in the continuous mode, and sloped sine function fit. This precession had a period of approximately 155 seconds.

occur at the frequency $\Delta\omega$, around 1 to 4 Hz, determined by the separation in frequency of the two modes, and correspond to instances where the wire vibrates in the direction of the field. In this way, if we can measure the decay profile, we can calculate the fraction of wire covered by vortex. The actual voltage from the wire gets amplified and fed into a lock-in amplifier (LIA) that filters the signal and extracts the amplitude of the signal near the wire's resonant frequencies. The output of the LIA does not show the actual oscillations of the wire but rather an envelope of their amplitude as the vibration precesses. Thus the measured decay profile (the output from the LIA) has the shape [3]:

$$\varepsilon_{env}\,(t) = \left|Ae^{-t/\tau}\cos\left[\left(\Delta\omega\right)t + \phi\right]\right| \tag{9}$$

Figure 1 shows decays envelopes measured at several circulation values. While the pulsed mode allows measurement of the circulation on the wire in a relatively straightforward manner, it has a significant limitation: it takes around ten seconds to acquire the circulation value. This means that phenomena with periods shorter than about 20 seconds cannot be reliably observed with the pulsed mode. One such phenomenon, Kelvin waves along the free vortex, has proven difficult to observe at any mode higher than its slowest.

B. Continuous mode

Instead of current pulses, we can apply a continuous signal to the wire at a selected frequency, often with amplitude much smaller than that of the pulse. We then measure the amplitude of the response signal from the wire. In this case the wire acts as a driven oscillator; matching the drive frequency to one of the resonant frequencies of the wire results in larger response signal amplitude. Whereas an oscillator with a single resonant frequency has a Lorentzian frequency-response profile, our

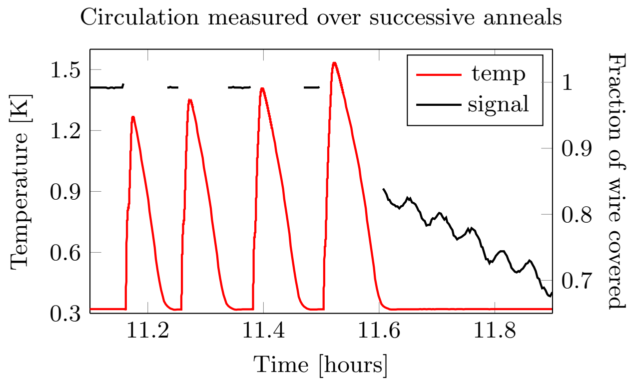

FIG. 4. Fraction of the wire covered by the vortex as a function of time, while four temperature anneals take place. At first the entire vortex lies along the wire in the metastable $n = 1$ state. We rapidly increase the temperature then decrease back to the base temperature 320 mK. While near the base temperature, we use the pulsed mode method, described in Section III, to measure the circulation. The vortex stayed pinned after the first three anneals, but the fourth anneal caused the vortex to dislodge from the wire, after which it began to decay further off the wire.

wire with two resonant frequencies has two peaks in a double-Lorentzian shape [3]. The signal in the frequency domain, as shown in Figure 2, relates to the signal in the time domain, Figure 1, through the Fourier transform.

The separation between the two resonant frequencies depends on the circulation: a larger separation corresponds to more of the vortex around the wire. The center of the two-peaked profile does not change with circulation. An increase in the temperature broadens the peaks, and at a sufficiently high temperature the two peaks become unresolvable.

This measurement in the frequency domain does not yet (as described above) provide any new information, nor information at a faster rate, than we could get from the pulsed mode: it usually takes even longer to measure a full frequency sweep than it does to measure a decay. But we have a trick: we know that, at constant temperature, the shape of the frequency-response profile should not change except for the separation of the peaks. We select a single frequency and observe changes in the amplitude. If the peak approaches the selected frequency, the amplitude will increase, and if the peak moves away the amplitude will decrease. From this, the whole double-Lorentzian profile can be inferred and thus a measurement of the circulation can be made at a high rate. The continuous mode measurements can, in principle, be made at a rate of about 1 Hz or better but the frequency resolution decreases as the rate increases. Figure 3 shows an example of a phenomenon successfully measured in this way.

C. Temperature Oscillations and Counterflow

Transport of heat in superfluid takes place at an extremely high rate due to a process known as counterflow. The explanation goes as follows: two containers of superfluid, held at different constant temperatures, have different superfluid fractions. A connection between the chambers allows exchange of fluid. Superfluid will flow continuously from the colder section to the hotter, and normal fluid will flow oppositely such that the total density stays constant. The normal fluid carries heat. As it arrives in the colder chamber, some of it converts to superfluid; some of the superfluid converts to normal fluid in the hotter chamber. This same process occurs in a single chamber with a temperature gradient, and larger gradients cause larger counterflow velocities. Additionally, the geometry of the container has an effect on the magnitude of the velocity: a temperature gradient across a long pipe with a small aperture at one end will have larger flow velocities through the hole than the same pipe with a large aperture.

Sufficiently large flow velocities can disturb a vortex pinned on the wire. The completely-pinned state of the wire has lower energy than a free vortex of the same length, so it will stay pinned for a long time. This state is actually metastable, because the vortex has a possible lower energy state: it could also not exist at all. Thus a sufficiently large perturbation to the vortex can knock it out of the metastable state and allow it to decay completely. In our experiment, we create temperature gradients of a variety of magnitudes for a variety of durations in order to reveal how large a perturbation it takes to depin the vortex.

The temperature controller allows us to set a temperature "setpoint" which it then attempts to reach and maintain through modulation of the helium-3 sorb temperature. Changes in the sorb temperature propagate through a long helium-4 infill line that ends at an aperture at the top of the cell. Normally the setpoint stays constant, but we can also change it rapidly at a selected rate. Practical limitations restrict the maximum rate at which we can actually change the experiment temperature in a controlled manner. We increment the setpoint periodically to establish an approximately constant temperature gradient at the cell aperture as the temperature increases. Eventually the setpoint ramp ceases, the setpoint resets, and the fridge temperature reaches a peak value after which it begins to return to the base temperature of $\sim$ 320 mK. Higher temperatures damp the wire motion and blur measurements of the circulation: in order to accurately measure the circulation along the wire after the anneal, the temperature must return close to the baseline.

Our objective is to determine and understand the mechanism that depins the vortex. Prior work, done in a different cell, showed that the likelihood of the vortex to depin from an anneal does not depend on the duration of the anneal. Further, it did not depend solely on the

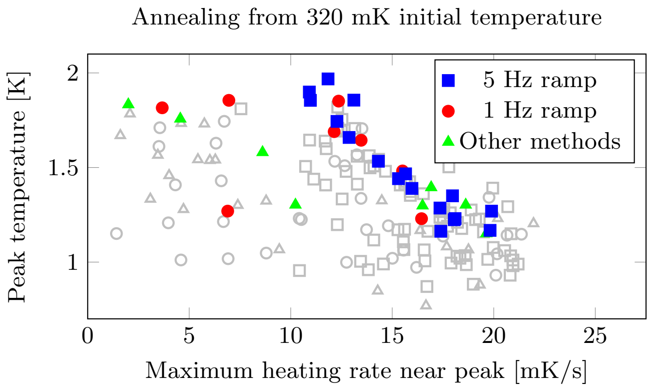

FIG. 5. All of this summer's annealing runs from $n = 1$, plotted by the peak temperature and the maximum heating rate measured within 200 mK of the peak temperature, averaged over one second. Colored shapes correspond to instances in which the vortex fell off the wire, and gray unfilled marks show when the vortex remained on the wire.

maximum temperature reached. It depended on a combination of the maximum temperature reached and the heating rate during the anneal. The vortex would fall off at lower temperatures when the heating rate was faster. This makes some sense if explained by counterflow: the magnitude of the flow velocity depends on the heating rate, and the vortices tend to be less stable at higher temperatures ($\gtrsim 1$ K).

In order to investigate this, we pick a heating rate then anneal the vortex to some maximum temperature and return to the base temperature. If the vortex stays on the wire, we repeat the anneal with similar heating rate but with a higher maximum temperature, and again we check to see if the vortex stays on. This method allows us to tell, based on when the vortex stays on and when it eventually falls off, that the difference between the penultimate and ultimate anneals likely caused the depin. We calculate the heating rate with a method described in Section IV A. Figure 4 shows one example of this process.

IV. RESULTS

A. Heating Rate Depin Threshold

We performed the process described above several dozen times across a variety of temperature ramp rates. Our tests included several different methods to control the temperature increase: for example, at first we would simply change the setpoint to a high temperature and allow the temperature controller to approach it quickly. This produced inconsistent temperature profiles with large variations in the rate, so we looked for more controlled means. The next method would increment the setpoint by a chosen step size once per second such that the temperature controller continually tries to catch up to the setpoint. Results improved, but often the temperature controller would fall far behind the setpoint, then apply a large amount of heat to catch up, and overshoot the setpoint significantly. We found that a faster setpoint update rate, now at 5 Hz instead of 1 Hz, combined with one-fifth size steps (to keep the actual temperature setpoint change per second unchanged), improved the results further. As a result, we used this final method for the remainder of the experiment.

Note that in order to quantify the heating rate of a temperature profile, we choose a definition for the heating rate. We calculate the heating rate as the highest rate, averaged over one second, measured in the highest 200 mK of the peak temperature. This definition comes from physical intuition: that the event that causes the vortex to dislodge likely occurs at the higher end of the temperature profile (the main difference between an anneal and the one before it). Other definitions tested included a simple average over the heating duration, the max one-second heating rate in the entire duration, the peak rate in the first half of the heating profile, the peak rate in the second half of the profile, and others. We found that all of these definitions produce very messy relations between the depins and the peak temperature and heating rate with no clear dependence, except the initial definition provided above. This definition arose from our intuition that the determining part of each anneal is its high-temperature behavior. If one anneal leaves the vortex on the wire and the next anneal has similar rate, reaches slightly higher temperature, but depins the vortex, it seems likely that the depin here depended on the difference between the two anneals. That is, the behavior near the peak temperatures seems to hold significant influence on the outcome. This, combined with the fact that this method yields consistent depin data,motivates our choice of heating rate definition.

Our results reveal a threshold in terms of heating rate and peak temperature. Below the threshold, the vortex tends to stay on the wire, and in successively hotter anneals the vortex tends to dislodge around the threshold. Figure 5 shows these results. At faster heating rates the vortices fell off the wire at lower peak temperatures. We collected data with several different heating methods, as described above; the later methods corresponded to the most consistent results. The threshold at which the vortex tended to fall off, however, did not change very significantly for different heating methods.

B. Inlet Aperture Size and Counterflow

When we heat the cell, we actually apply the heat to the sorb. Through an indirect process, heat reaches the cell by way of the helium infill line: the long, narrow tube that we use to put in and take out the helium from the cell. We hypothesize that counterflow causes the vortex to fall off the wire; this may occur near the aperture of the infill line. The temperature gradient between the infill line and the fluid in the cell sets up counterflow in the infill line and around the aperture, and the magnitude of this flow depends on both the heating rate and the geometry of the infill line and aperture. If the majority of the infill line were kept the same, but the aperture size changed, then we would expect that the magnitude of counterflow velocity would vary inversely with the aperture size; this hypothesis predicts that the vortex should fall off more easily with smaller apertures. If very much of the infill line diameter changed, then more complicated changes in the counterflow velocity should occur; a change to only the aperture should not significantly change the behavior of the fluid far away in the rest of the infill line, and instead only affect the flow near the aperture itself.

The cell used for this summer's experiments had a larger aperture than that of a cell used for similar annealing experiments conducted several years ago. The data from that earlier cell show that the vortex tended to fall off at lower temperatures than it did with this summer's cell. Even anneals at $n = 1/2$ (which generally fall off at higher temperatures than anneals at $n = 1$) tended to fall off at peak temperatures below 1.5 K in that previous cell. This contrasts sharply with the observations this summer, as Figure 5 shows that a number of runs stayed pinned well above 1.5 K.

V. CONCLUSIONS

Our results show a vortex depin threshold that depends not only on the peak temperature achieved but additionally on the heating rate near the peak. For faster heating rates, the vortex falls off at lower peak temperatures. This matches our hypothesis of counterflow as the cause of the depin; in our interpretation, counterflow near the aperture interacts with small vortices pinned to the cell walls in such a way as to increase their size such that they, then, disturb the vortex on the wire. The fact that the likelihood of the vortex to fall off depends on the cell aperture size lends further support to our picture: the larger aperture on the newer cell should cause smaller counterflow velocities and less disturbance of the vortex. We therefore propose that the pinned vortices depin as a result of counterflow and that further experiments that vary the magnitude of velocities by modulation of heating rate or geometry may provide valuable insight on the stability of the pinned state. Also, future work may determine how to quantify the actual fluid velocity given the measured heating rate.

VI. ACKNOWLEDGEMENTS

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