Staircaselike Suppression of Supersolidity under Rotation

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There are a number of distinct signatures of superfluids, one of which is the appearance of quantized vortices. There have been some attempts to understand the putative supersolid ^{4}He in the vortex framework, but no conclusive evidence that supports the existence of the vortices has been reported. Here, we investigate the rotation velocity dependence of the torsional oscillation of solid ^{4}He at various temperatures. The velocity sweep reveals intriguing periodic staircaselike features below about 300 mK. The staircase patterns show remarkable periodicity, and we interpret these patterns as a consequence of vortex injection. However, there are some features that cannot be accounted for with simple injection of vortices into superfluid, and further investigation is required.

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Liquid helium flows without viscosity below 2.17 K. There have been a number of studies on whether or not superfluidity can coexist with solidity in helium [1–13]. In a recent attempt to find such an effect, Kim and Chan measured the resonant period of a torsional oscillator (TO) containing solid helium and found an intriguing phenomenon: a fraction of solid helium apparently decoupled from oscillating bodies marked by the reduction of the resonant period [14,15]. This was interpreted as the nonclassical rotational inertia (NCRI) [4] of solid helium.

Despite the initial excitement of the possible discovery of a supersolid, it turned out to be rather difficult to replicate the intrinsic characteristics of superfluids with solid ^{4}He [16–21]. An interesting development in the field came from a somewhat unexpected front of measuring the shear modulus of the solid. The shear modulus showed an anomalous increase below 200 mK with a striking similarity to the temperature dependence of the NCRI [22].

A number of studies were carried out to try to identify the connection between the two phenomena [23–25]. Reppy tested the effect of crystal quality on torsional oscillation by measuring the oscillation period before and after applying large amounts of stress, thereby introducing dislocation lines into solid helium [24]. From the fact that the high temperature TO period is affected by the extra dislocations created by the stress whereas the low temperature period stays unchanged, they concluded that the drop in the period is simply attributed to stiffening of the solid at low temperatures [24,26].

A test performed by Kim *et al.* [25], however, shows contradicting results to that of Reppy. They measured the influence of shear modulus change on the TO period within a single sample cell. The resonant period of TO was not affected by the softening of solid helium in the TO cell. Although this experiment cannot provide a thorough understanding of the connection between the two effects, it indicates that the TO resonant period is not simply measuring the elastic properties of the solid.

A fundamentally different approach has been taken by Choi *et al.* [27]. They imposed dc rotation on top of torsional oscillation and observed the irrotationality of superfluid affecting the TO response. They also examined the effect of rotation on the shear modulus independently at low temperatures and found that the TO response is essentially different from the shear modulus change.

In this Letter, we present more intriguing quantized features in the response of TO under dc rotation. This observation provides more concrete evidence that the TO response under dc rotation is not merely the consequence of solid stiffening. The experiment was performed on the identical TO and rotating cryostat as those used in previous experiments [25,27].

A number of TO measurements were performed with various angular velocities to investigate the nature of suppression in the NCRI fraction (NCRIF) under rotation. We first set the rotation speed to 3.5 rad/s at 500 mK and then cooled the sample down to target temperatures, e.g., 15 mK. Once the target temperature was reached, we swept the velocity down by a small step of 0.05 rad/s, waiting for 1 h at each step to ensure that the TO reached its equilibrium period and amplitude.

The resonant period and amplitude of a TO with solid helium do not change monotonically with rotation speed (see Fig. 1). The most astonishing observation is the staircaselike features marked by the orange arrows. They are periodic in dc rotation velocity, and the periodicity in the angular velocity is about 0.85 rad/s. With each step, resonant period suppression is about 4 ns.

At small angular velocities below 0.85 rad/s, there are smaller steps. The feature appears to be less prominent than that of the high velocity steps. To investigate detailed structure of these features, the velocity was swept with a discrete change of 0.014 rad/s with 1 h equilibrating time at each point, between the angular velocity of 0.65 and 0 rad/s. The smallest steplike kink in both the period-velocity plot and the amplitude-velocity plot appears at

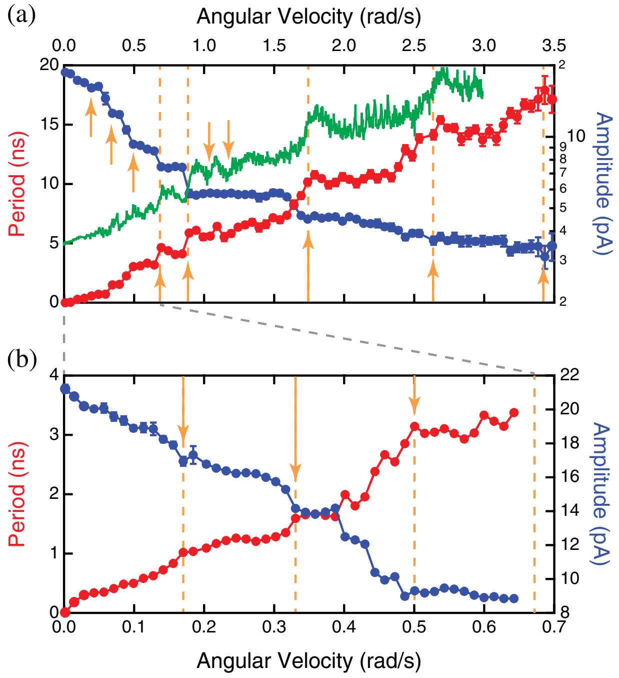

FIG. 1 (color online). TO period and amplitude upon velocity sweep down at 15 mK. (a) Staircaselike features are present in both the period data (red circle, left axis) and the amplitude data (blue circle, right axis). The velocity change is carried out in discrete steps. The green curve is data taken by continuous velocity sweep, and it is displaced by 5 ns for clarity. (b) The velocity sweep was performed with a finer step size below $\omega = 0.7$ rad/s.

0.17 rad/s with a period step of ~1 ns. This feature is again periodic up to 1.2 rad/s.

This is an extremely time-consuming process, and a relatively faster procedure was taken for the bulk of our data. After setting the velocity at 500 mK and cooling helium down to the target temperatures, we swept velocity down continuously to zero in the time span of 9 h. We then swept the velocity back up to 3 rad/s also in 9 h. Comparison of our data taken by two different procedures confirms that the continuous velocity scans were, in fact, sufficiently slow to guarantee quasistatic equilibrium throughout the whole process as shown in Fig. 1(a).

These staircaselike features are not an artifact introduced by mechanical vibration accompanying the rotation. We measured the frequency spectrum of the vibration level, over the frequency range 10–1000 Hz, at the mixing chamber where our experimental cell was mounted. Above 50 Hz, the vibration level with and without rotation shows no change. Below 50 Hz, there was a slight increase in vibration as large as about 5 nm. However, when converted to velocity, it is only about 100 nm/s. In addition to that, this frequency range is too low to have any effect on our torsional oscillator, whose resonant frequency is around 1 kHz with a high Q factor of $\sim 10^6$.

As dislocation pinning and solid stiffening are two of the widely considered possible mechanisms for the TO response, it is necessary to examine whether these effects are responsible for the observed behaviors or not.

When the internal stress in the solid helium is on the order of 0.1 Pa, it is found to cause unpinning of dislocation lines and cause slippage of the solid [22,26,28]. Intermittent slippage of dislocations may cause a staircase-like change in the TO period. In considering such a scenario, we need to look into two primary sources of stress in a rotating system. One is tangential stress σ_t, coming from the change in the rate of rotation, and the other is radial pressure σ_r, due to centrifugal force.

The tangential stress σ_t is proportional to $R\alpha$, where R is the radius of the TO and α the angular acceleration of the cryostat. The radial stress σ_r is proportional to $R\omega^2$, where ω is the angular velocity.

The aforementioned extraordinary features are reproducible at given angular velocities, regardless of the velocity sweep rate. This is strong evidence that the phenomenon is not caused by the tangential acceleration. Besides, the upper limit of the tangential stress in our measurements is approximately 10^{-3} Pa, typically orders of magnitude smaller than the radial stress.

Radial stress σ_r is estimated to range from zero to 0.01 Pa under rotation up to 5 rad/s, the maximum angular speed in our measurements. This is smaller than the stress level known to cause solid slippage or the inertial stress caused by the torsional oscillation. Accordingly, it is difficult to reconcile a discrete change in period with the explanation based on dislocation slips.

The change of NCRIF was also tested by the group in Cornell University during the free induction decay, that is, continuous decrease of ac oscillation velocity [29]. The TO response exhibits a monotonic decrease without any periodic steps during the free induction decay studies. If the steplike change is coming from sudden slippage of dislocations at certain stress levels, then it should be manifested not only in dc rotation velocity sweep but also in the free induction decay measurements.

A tempting interpretation is that these steps are a manifestation of an uncharted quantization in solid helium. The natural quantization signature under rotation could be the entrance of quantized vortices or quantized circulation. We can define two types of critical velocities: Ω_{C1} and Ω_{C2} mark the first reduction in the NCRIF and the complete destruction of the NCRIF, respectively.

The quantum circulation increases by h/m and induces the periodic suppression of superfluidity. Within the framework of general superfluidity, we can calculate the critical velocity for injecting a single quantized circulation from the equation $\Omega_{C1} \sim \hbar/mR^2$. The critical angular velocity is approximately 2.5×10^{-4} rad/s with our TO cell geometry of $R = 8$ mm. In this calculation, we consider only solid helium in the annular channel, since no chemical potential gradient between two ends of the center channel is present.

Experimentally, Ω_{C1} is identified with the first discrete kink in period-velocity measurements marked by the first orange arrow in Fig. 1(b). Given the complexity of the system, the supersolid is unlikely to be a straightforward superfluid. Nonetheless, the discrepancy between the measured value of $\Omega_{C1} = 0.17$ rad/s and the estimated critical velocity of $\hbar/mR^2 = 2.5 \times 10^{-4}$ rad/s is not trivial.

The presence of a large amount of normal solid component may play the role of a solid matrix through which the superfluid component has to pass and thereby increase tortuosity. This may be the partial source of the discrepancies. Another possibility is the supersolid being an inhomogeneous superfluid network [30]. In this framework, the phase coherence is not necessarily established over the entire annulus but rather closed paths formed by the superfluid network. For example, if the effective diameter of such paths is close to a few micrometers, then the critical velocity can be estimated to be as large as 1–10 mm/s.

The value of Ω_{C2} is even more troublesome. We cannot determine Ω_{C2} purely from our measurements due to the technical difficulty in rotating the cryostat beyond 5 rad/s. We must therefore extrapolate our data. As shown in Fig. 2, barring the staircaselike structures, the NCRIF decreases linearly with increasing rotation velocity. The linear suppression can be connected to the linearly increasing number of vortices as the rotation velocity increases.

By extrapolating our data to the point where NCRIF completely vanishes, we find Ω_{C2} to be about 13 rad/s. This corresponds to the injection of about a few tens of thousands of vortices within the superfluid framework. The obtained critical value appears to be extremely small compared to that of regular superfluid, whose Ω_{C2} is on the order of 10^{12} rad/s. This warrants further investigation.

We note that the rotation velocity dependence is generically different from that of ac oscillation induced suppression, which exhibits $\log v$ dependence. This discrepancy may arise from the different nature of dc rotation induced suppression of NCRI from ac oscillation induced suppression. The observation is not inconsistent with the previous conclusion that ac oscillation and dc rotation may play different roles in suppressing NCRIF [27].

We also observed hysteresis in NCRIF upon a down sweep followed by an up sweep of rotation velocity below 50 mK. Hysteretic behavior is one of the very unique features in supersolidity not seen in the conventional superfluids. As shown in Fig. 3, the hysteresis becomes more evident at lower temperatures. The hysteretic tendency is similar to the behaviors reported by Aoki, Graves, and Kojima [31] and Choi *et al.* [32]. They followed similar procedures with an ac oscillation velocity sweep in their works instead of a dc rotation sweep. Although no staircaselike features were observed in their works, they observed hysteresis opening up between the velocity down sweep and velocity up sweep at temperatures below about 70 mK.

Experiments on relaxation dynamics of a TO showed extended relaxation below about 70 mK, which exhibited strong correlation with the appearance of history-dependent behaviors [32,33]. To see if such linkage is present with a change in dc rotation velocity, we have investigated the relaxation of the TO response at various temperatures under the sudden change of rotation velocity. With a sudden drop in rotation speed, the resonant period and amplitude response was immediate and no relaxation was seen. On the other hand, a sudden increase in rotation velocity showed a measurable relaxation process. The asymmetry in the behavior might be a reflection of the hysteresis.

We studied the relaxation dynamics in more detail by raising the velocity with a discrete step from zero to 2 rad/s and zero to 4 rad/s. There is a very sharp increase in period right after the rotation velocity change within the time scale of about 100 s. After the abrupt change, there is

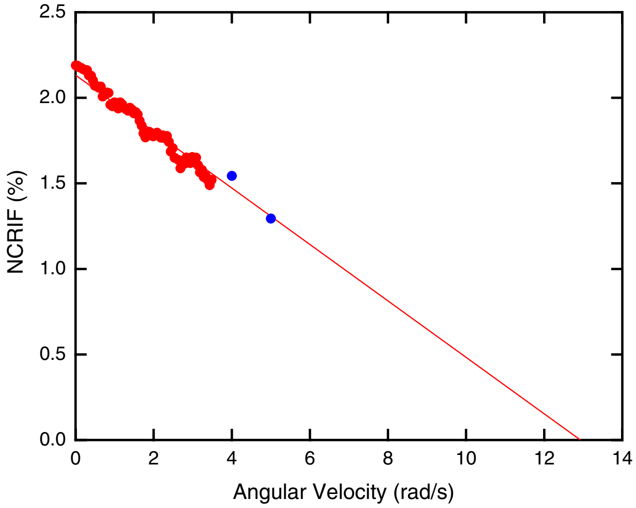

FIG. 2 (color online). Linear extrapolation of the NCRIF against angular velocity measured at 15 mK. The extrapolation of the data predicts the NCRIF to be completely suppressed at about 13 rad/s. Two blue data points are obtained from the temperature sweep performed under dc rotation at 4 and 5 rad/s.

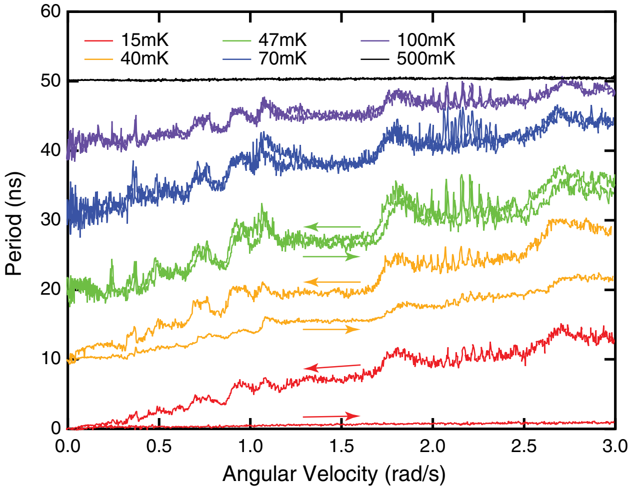

FIG. 3 (color online). Gradual development of hysteresis with decreasing temperature. The velocity sweep shows no observable hysteresis above around 50 mK. A small amount of hysteresis opens up below 50 mK and becomes more prominent as the temperature is reduced.

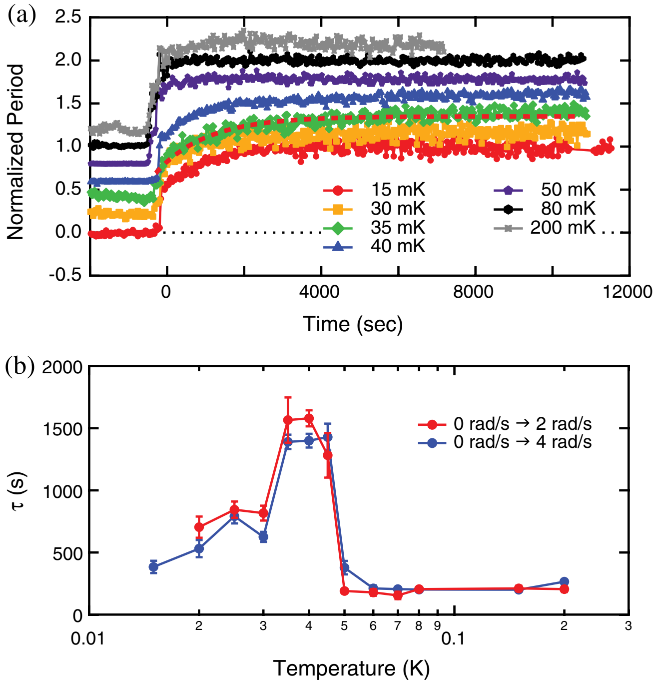

FIG. 4 (color online). (a) Relaxation in period after a sudden change in dc rotation velocity from 0 to 4 rad/s at various temperatures. The period change is normalized at each temperature and separated by 0.2 for visibility. The red dashed curve is a fit to 35 mK data using $y = y_0 + Ae^{-t/\tau}$. (b) Temperature-dependent relaxation time τ of a TO upon changing the dc rotation speed from 0 to 2 rad/s (red circle) and 0 to 4 rad/s (blue circle).

a relaxation process that fits to exponential decay quite well with a much shorter time constant than that found in the ac oscillation induced relaxation.

The TO finds its new equilibrium value of the resonant period quite rapidly at temperatures higher than 50 mK. On the other hand, a substantial extension of the equilibration time is detected below 50 mK. This, in fact, suggests that the extended relaxation may be connected to the hysteresis as with ac oscillation. However, the maximum at around 40 mK and no diverging time constant at lower temperatures separate our observations from the previous relaxation studies [31,32,34].

It is interesting to note that the overall temperature dependence of the relaxation time constant as displayed in Fig. 4(b) is astonishingly similar to that of the unusual change in the isochoric compressibility of solid ^{4}He [35], although the extremum temperature is slightly lower. The difficulty of fully understanding all these phenomena is compounded by the fact that the superfluid scenario has no solid theoretical grounds and many questions are still open. Our study clearly warrants further investigation of solid helium under dc rotation.

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