Characterization of the Surface of Moving Solid $^4$He

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Abstract Crystal grains of solid $^4$He can move in relation to each other even when embedded inside the solid [1,2]. In this work, we characterize a macroscopic motion of solid hcp $^4$He composed of such grains. Motion is induced by applying an external torque to the solid contained inside an annular channel mounted on a torsional oscillator. In order to characterize the surface of the moving solid, we developed an in situ flow detection method using a sensitive “microphone” embedded in the wall of the channel. Motion is detected by counting the vibrations induced by rows of He atoms moving past the microphone. Such vibrations were detected only at $T = 0.5$ K, our lowest temperature. At this temperature, the measured dissipation associated with the solid He is zero within our accuracy. Our results indicate that the orientation of the surface of the moving solid is the (0001) basal plane of the hcp structure. At $T = 0.5$ K, we found that for speeds $<7 \mu$m/s, the solid flows without detectable friction.

Keywords Solid helium · Friction · Quantum friction · Acoustic Force Microscopy

1 Introduction

Solid $^4$He, the archetypal quantum solid, has been the subject of intense study in recent years. Aside from a search for supersolidity [3], the existence of which is currently under debate [4–6], there is an ongoing effort to explore and understand the unique elastic [7] and plastic [8–10] properties of crystalline He at very low temperatures. We are particularly interested in understanding the friction between crystallites of He
moving past each other. Internal friction in a static polycrystalline solid He was investigated in the past, and was found to result from the dynamics of pinned dislocations as described by the Lucke–Granato model [11,12]. However, the classical friction problem of one solid mass moving against another, was not yet addressed in solid He. This is an interesting issue, since beyond classical friction, there are several predictions regarding what the friction would be in the quantum regime. One proposed friction mechanism comes from the Van der Waals force, due to zero-point charge fluctuations [13]. Another mechanism involves phonon–phonon interaction while the phonons populating one of the masses are Doppler shifted due to the relative motion [14]. Since solid He exists only under pressure, the classical layout of a tabletop friction experiment cannot be realized. We have however accidentally stumbled upon a way to perform such friction experiments in the way described below. Preliminary results [15] indicate that the friction between two He crystallites is extremely low, yet it can be measured with good precision. We hope that such experiments may pave the way to a future research of fundamental mechanisms of quantum friction. The experiment described here is a first step in this direction, intended to characterize the interface between two moving masses of solid He. The paper is organized as follows: we first describe our crystal preparation. This subject is similar to the work discussed previously and is included here to make the paper self contained. The second part describes our new in situ motion detection method. The third and final part includes the experimental results and discussion thereof.

2 Experimental I: Growth and Disordering of $^4$He Crystals

Our interest in doing the work discussed here began with neutron diffraction experiments on bcc solid $^4$He. During these experiments we grew large (7–10 cm$^3$) single crystals, which sometimes transformed into polycrystals due to some thermal or mechanical stress. In those cases, we noticed that individual crystallites which are part of a polycrystalline solid can spontaneously change their spatial orientation while embedding in the surrounding solid [1]. These orientation changes seemed to be driven by ambient noise, either vibrational or thermal. Consequently, these orientation changes of the solid grains persisted for the duration of the experiment (on an order of a week). Usual solids deform under applied shear stress. Seemingly spontaneous motion of macroscopic solid crystallites inside a solid matrix is unusual, and seems to be unique to solid He. The same unusual behavior was later observed [2] in polycrystalline hcp $^4$He. In contrast to polycrystals, single crystals of solid He are stable in the sense that they do not change their orientation at all. In the neutron scattering setup, the cell containing solid He was static and the ambient stress field was caused by mechanical vibrations or thermal noise. To see how this spontaneous mobility of the polycrystalline solid manifests itself under a controlled external stress, we decided to study similar crystals grown inside an annular channel forming a part of a torsional oscillator (TO). In this setting, the solid is acted upon by an external torque applied by the moving walls of the TO.

We grow single crystals of solid hcp $^4$He of commercial purity (0.3 ppm $^3$He) inside an annular channel forming part of the TO [17,18], shown in Fig. 1. The channel width
is 2 mm, and its height is 10 mm. The channel is filled through a heated filling line, 0.25 mm i.d., connected to the top of the cell. Heating the filling line ensures that the lowest temperature is at the bottom of the cell, nearest to the cold plate, and so the solid nucleates there. We use the same growth method developed during the neutron scattering experiments. Crystal growth takes place at a constant temperature and pressure, on the melting curve, by periodically adding small amounts of helium into the cell. The TO is thermally attached to a $^3$He cryostat which provides a stable platform at any temperature between 0.5 and 3 K. The measured contribution of a single crystal of $^4$He to the moment of inertia of the TO agrees very well with the calculated value. There is no increase in the internal dissipation of the TO associated with a single crystal. Hence, within our accuracy a single crystal behaves like a perfect rigid body moving with the TO. Figure 2 shows how the experiment is monitored during the final stages of crystal growth. Once the cell is full of solid, we block the filling line with solid as well. Next, we stress the crystal further by cooling the cell by 50–100 mK. Thermal contraction of solid He is prevented by the central post of the annular sample space. As a result, internal stress is generated, large enough to cause the crystal to disorder and transform into a polycrystal. This behavior is consistent with what we observed in neutron scattering experiments [1]. It is important to point out that the crystal can be disordered only after the cell is entirely filled with solid. As long as any liquid remains in the cell, it acts as a buffer which relieves stress, and the single crystal is stable. Even with one drop of liquid in the cell, we were able to maintain...
Monitor data during final stages of growth and subsequent disordering of a single hcp crystal grown on the melting curve at a temperature close to 1.8 K. Time is measured from the beginning of crystal growth. During growth, small quantities of He are added periodically to the cell through a heated fill line, causing the pressure (blue symbols, right axis) to increase momentarily and then relax back to the melting pressure as liquid is converted into solid. Simultaneously, the resonant period of the TO (black symbols) increases as additional solid mass is coupled to the oscillator. After about 55 h, the cell is full of solid and the pressure is increased further to block the filling line with solid. The heat coming through the filling line is cut off and the crystal begins to disorder. At 60.2 h, the temperature (red symbols) of the cell is lowered to 1.7 K. This causes the crystal to disorder further and the period of the TO spontaneously to decrease, as if some of the solid becomes decoupled from the motion of the cell. This is what we refer to as “mass decoupling” (Color figure online).

Figure 3 shows in more detail how the transformation of a single crystal to a polycrystal affects the TO. Once the disordering is complete (time > 60 h), the resonant period (black symbols) has decreased and in parallel, the dissipation of the TO (green symbols) increased. First, we discuss the resonant period. A decrease of the period of the TO can be caused by several reasons: (a) partial melting of the solid. We start to cool with both the cell and its filling line already full of solid. Cooling, if anything, converts liquid into solid, not the other way round. Hence, option (a) is not possible. We checked this directly by intentionally introducing some liquid into the cell. The polycrystal immediately annealed, the period of the TO returned to that of a cell filled with a single crystal, and the decoupling effect vanished. Option (b) is that the resonant frequency increases due to an increase of the effective torsion constant of the TO. This can happen if the shear modulus of solid He increases. The influence of the elastic properties of solid He on the resonant frequency was first discussed by Clark et al. [16], in conjunction with the search for supersolidity [3] at low temperatures. To see whether this possibility applies in our case, we carried out a similar analysis of our system and for our temperature range using Finite Element Analysis. This analysis is described in detail in the Appendix. The conclusion is that various effects related to the shear modulus of solid He affect the resonant period of the TO by 1–2 orders of magnitude less than the changes we observe. Consequently, effects related to the shear modulus cannot explain our results either. We are therefore left with option (c),
that the effective moment of inertia associated with a polycrystal is smaller than that of a single crystal. This will take place if part of the solid does not move as a rigid body with the TO and becomes effectively decoupled from the motion of the walls. In the frame of reference of the TO, this decoupled solid moves relatively to the wall, in consistency with our observations during the neutron scattering experiments.

We now consider the dissipation of the TO, shown in Fig. 3 as green symbols. The dissipation is given by \( \omega_{TO} \times \left( \text{stored energy} \right) / 2\pi Q \), where \( \omega_{TO} / 2\pi \) is the resonant frequency of the TO and \( Q \) is the quality factor. At times \(< 55 \) h, while the cell is being filled with a single crystal, the dissipation decreases. This indicates that the single crystal behaves as a rigid body and the remnant dissipation is associated with the fluid remaining in the cell. When the cell is entirely filled with solid, the dissipation reaches a minimum. Upon disordering the crystal, the dissipation increases, and after several hours reaches a steady state. The increase of the dissipation indicates that with a polycrystal, there is additional friction associated with internal motion within the solid. Based on neutron diffraction experiments [1], we associate the time-dependent changes of the dissipation with orientation changes of the polycrystal inside the cell. The reorientation process gradually lowers the internal dissipation from its peak value.

To calculate the dissipation, we use the moment of inertia of our TO which is about 40 gm cm\(^2\). Taking a typical tangential velocity of 10 \( \mu \)m/s, the energy stored in the TO is in the \( 10^{-5} \) erg range. We found that the dissipation associated with the oriented polycrystal is temperature dependent [15]. At temperatures above 1 K, the dissipation is in the \( 10^{-7} \) erg/s range. At our lowest temperature of 0.5 K, it decreases to \( 10^{-9} \) erg/s, which within our precision is the same as that of an empty cell. Hence, at 0.5 K the internal friction between the decoupled solid and the solid moving with the wall is zero within experimental accuracy. Systematic measurements of this dissipation can tell us about the internal friction, a subject for our future work.

Finally, we point out the necessity of growing single crystals and turning them into oriented polycrystals. For comparison, we grew unoriented polycrystals inside the cell instead of single crystals [19]. In this case, we observed 1% of mass decoupling instead of 10–25%. Hence, starting with a single crystal is essential to maximize the mass decoupling. We also point out that the transformation of a single crystal to a polycrystal occurs very close to the temperature at which a particular crystal was
grown. We can grow single crystals and disorder them at any temperature of choice between 1.1 and 2.5 K, so this transformation is a thermomechanical effect, not a phase transition. In particular, we see no apparent connection between our work and the search for supersolidity [4–7] which is done at much lower temperatures.

3 Experimental II: Microphone Study of the Motion of Solid $^4$He

So far, the information regarding motion of the solid relative to the walls of the TO was indirect, inferred from the change of the moment of inertia of the TO. To learn more about what actually goes on inside the cell, we developed a new method to study this motion in situ. Specifically, we designed a sensitive “microphone” which we incorporated into the inner wall of the annular sample space inside the TO (see Fig. 1). Essentially, the microphone is a plate capacitor with one plate which is movable. The static electrode is a 2-mm diameter brass disk, embedded in the central post as shown in Fig. 1. The movable electrode is a 15-$\mu$m-thick metalized polyvinyl strip charged with 150 V DC bias with respect to the static receiver electrode. The polyvinyl strip is glued around the central post of the TO, except for the section near the brass disk which is suspended inside the sample space, in parallel to the static electrode, at a distance of several hundred microns. To make the device more sensitive, the suspended section of the movable electrode is not under any tension. Motion of the charged movable electrode will induce a current in the receiver electrode which would be detected by a current preamplifier. During the experiment, the gap between the two electrodes is also filled with solid He, so that the effective mechanical compliance of the microphone is similar to that of solid He. To create a framework in which we can analyze experimental results, we propose a kinematical working model illustrated schematically in Fig. 4. We assume that at some distance $D$ from the wall of the annular channel there is a grain boundary separating the solid moving with the wall and the decoupled solid. Both electrodes of the microphone are embedded inside the solid moving with the wall. Lateral motion of the decoupled solid along this grain boundary will generate a time-dependent force between the two surfaces resulting from the periodicity of the lattice potential. The strain generated by this force can be detected by the microphone. The extent of the lateral relative motion at the interface is controlled by the oscillation amplitude of the TO. This amplitude is small, typically a few lattice constants. On that scale, there is a reasonable chance that the interface will contain no defects. In this case, this motion will induce a periodic vibrating strain at the microphone with a frequency $f = V_{\text{rel}}/d$, where $V_{\text{rel}}$ is the relative lateral speed between the wall and the decoupled solid and $d$ is the spacing between nearest rows of atoms of the moving solid. The time-dependent signal of the microphone can be Fourier transformed to determine this frequency, and thus yield information about the interatomic distance and the flow speed.

The expected strain amplitude near the movable electrode should be much less than a lattice constant of solid He. Modeling the microphone as a capacitor, its measured noise floor is low enough to detect vibrations down to the $10^{-11}$ m range (a few % of a lattice constant). The bandwidth is 250 kHz, limited by the current amplifier. Such bandwidth is required since for a typical relative speed of several $\mu$m/s, the expected
frequency $f = V_{rel}/d$ is tens of kHz, the exact value depending on the interatomic distance $d$.

The principle of the method proposed here is similar to atomic force microscopy (AFM), which unfortunately cannot be applied to solid He, since the He–He atomic bond is so weak that the interaction with any AFM tip would destroy the surface of the He crystal. In our case, the movable electrode, effectively the “AFM tip”, is coated by solid He, as are all the internal surfaces of the sample cell. Thus, its interaction with crystal grains moving at the interface (Fig. 4) should be that of solid He with solid He, which at small stress as we use is non-destructive. One additional inconvenience is that unlike with an AFM, where one scans the sample until a clean surface is found, we have to grow a new crystal to try again. Growth and characterization of a polycrystal typically takes more than a week.

A priori, there is a significant probability that the experiment would yield a null result even in the presence of flow of the solid relative to the wall. Referring again to Fig. 4, if the distance $D$ between the microphone and the spontaneously formed grain boundary is large, the vibrations at the microphone may be too weak to detect. Second, the lateral size of our microphone is about a mm, while the typical size of the crystal grains making up the polycrystal is a fraction of a mm [18]. Vibrations originating from different grains are not coherent, and so the total signal of the microphone would average to zero. Based on the analogy with an AFM, it is likely that a non-zero signal
would be detected only if some small part of the microphone, smaller than a single grain (0.1–0.3 mm), is close enough to the grain boundary. Our samples consist of similar, but not identical single crystals. Our hope was that some of these crystals will satisfy the conditions listed above.

Detecting the vibrations is further complicated by the fact that they originate at the atomic scale and so are not phase correlated with the oscillatory motion of the TO. Therefore, simply averaging the signal of the microphone over many cycles of the TO sums to zero. Instead, we averaged the absolute value of the Fourier transform of the microphone signal. This procedure makes the data insensitive to the phase of the signal. However, one problem which arises in this case is that the random noise does not cancel. Therefore, the power spectra contain contributions of both signal and noise. In order to extract meaningful results, one first needs to understand the response and noise characteristics of the microphone. We studied the background noise by analyzing the spectra obtained with the cell either empty or filled with liquid. A typical set of spectra acquired under different conditions is shown in Fig. 5. We first consider the spectrum of an empty cell (red symbols). One can see that the noise spectrum is basically flat with several resonance-like features. We believe that these are acoustic “plate resonances” of the polyvinyl electrode, which like everything else freezes and becomes rigid at low temperatures. These resonances are excited by the ambient broadband electrical field noise which is always present. Since the movable electrode is biased at 150 V, the electrical charge on it would react to electric fields. Filling the cell with liquid He (black symbols) reduces the amplitude of these resonances, but does not affect their frequency. To see if these resonances couple to sound waves in He, we changed the pressure of the liquid between SVP and 25 bars. The speed of sound in liquid He changes from 237 m/s at SVP to 365 m/s at 25 bar, but there was no change in the frequencies of the resonances. The only effect seen in Fig. 5 is that the amplitude of the resonances is reduced. Hence, the decrease of the amplitude of the resonances in the presence of liquid is due to mass loading of the movable electrode, and there is no coupling of the microphone to sound waves in He.

![Fig. 5 Typical response spectra of the microphone signal under different conditions. The data set taken with a disordered crystal in the cell was acquired at a wall speed of 5.6 µm/s (Color figure online)](image-url)
Filling the cell with a single crystal (blue symbols) does not produce any additional features in the spectrum in Fig. 5. However, it reduces the amplitude of the resonances sharply. This is to be expected since single crystals are rigid and immobilize the electrode more effectively than the liquid. Finally, these plate resonances showed no dependence on temperature or on the speed of the TO. The only effect the TO has on the spectra is one point near zero frequency in Fig. 5, which results from feedthrough at the drive frequency (360 Hz), and is the same for all data sets.

Having understood the background, we next look for a signal arising from a moving disordered crystal. Such a spectrum is shown in Fig. 5 by violet triangles. We first notice that the intensity of the plate resonances of the electrode is somewhat higher with a disordered crystal than with a single crystal. This is reasonable, since the disordered crystal is not as rigid as a single crystal and so is less effective in immobilizing the electrode. More importantly, with a disordered crystal we see an additional feature which was not there in the single crystal or empty cell spectra, namely a broad peak around 50 kHz. When referred to the input, the magnitude of this peak represents motion of the electrode in the $10^{-11}$ m range, which is the correct magnitude for the signal we expected. The frequency at which the peak appears is also in the region we expected. The spectra acquired with disordered crystals were the only ones which depended on the speed of the TO. To extract useful information, we divided each power spectrum obtained with a disordered crystal by that of its parent single crystal which is static. This procedure allowed us to remove most of the frequency dependence of the background using the single crystal spectrum as an effective gain function. The features which emerge under this procedure are the excess vibrations due to the motion of the polycrystal relative to a static single crystal.

4 Results and Discussion

In total, we grew and measured 15 hcp oriented polycrystals. Most of the parent single crystals were grown on the melting curve between 1.2 and 1.4 K. Upon disordering, all the polycrystals showed a similar decoupling mass fraction. Excess vibrations of the kind shown in Fig. 5 as violet triangles were detected in three polycrystals. This indicates that although all the polycrystals showed the same mass decoupling so that all of them move relatively to the wall, the stringent conditions for detection of the motion by the microphone are satisfied only by some of them. In addition, such vibrations were seen only at $T=0.5$ K, our lowest temperature, where the dissipation of the TO was close to that of an empty cell. More specifically, we did measurements at 0.1 K intervals, and already at 0.6 K we saw nothing above the background shown in Fig. 5.

The data shown in Fig. 6 represent a typical spectrum of excess vibrations of a disordered crystal relative to its parent single crystal. The main feature is a broad peak around 50 kHz. To understand the origin of this peak, we consider the case where the moving surface is free of defects and well-defined vibrations exist. During each cycle of the TO, the speed of the solid relative to the wall changes between zero and some maximum value $V_{\text{max}}$ as $V(t) = V_{\text{max}} \cos(\omega_{\text{TO}} t)$. The instantaneous frequency of vibrations $f$ would therefore change between zero and $f = V_{\text{max}}/d$. The intensity of vibrations at a given frequency $f$ in the spectrum depends on the amount of time
the TO spends at a particular speed $V$ during each cycle. We therefore calculated the probability of finding the TO moving at a certain velocity at some random time. This probability is proportional to the time $dt$ spent at each velocity between $V$ and $V + dV$. It can be calculated from the derivative of the inverse time dependence of the speed, $t(V) \propto \arccos(V/V_{\text{max}})$. We find that the resulting probability density function $p$ depends on speed as $dt/dV \propto p(V) = 2/(\pi \sqrt{1 - (V/V_{\text{max}})^2})$. Consequently, the power spectrum of the vibrations shows a divergence at a frequency $f = V_{\text{max}}/d$.

In the actual data we expect that finite frequency resolution and noise will wash out the singularity, but simulations done in the presence of noise indicate that a peak still exists. The result is shown as the inset in Fig. 6. We expected the peak frequency $f$ to depend on friction. For a given $V_{\text{wall}}$, the highest value of $f$ will be measured if the friction is zero. In this case the decoupled solid does not move at all, namely $V_{\text{max}} = V_{\text{wall}}$, and so $f = V_{\text{wall}}/d$. In the limit of high friction, the wall and the solid move together and $f = 0$. With finite friction, for example of the stick-slip type, there may be no well-defined frequency associated with the relative motion.

Observing a well-defined peak of excess vibrations at some frequency confirms that (a) the solid inside the cell is indeed moving relative to the wall. (b) the surface of the moving grains is free of defects on the scale of the motion.

In Fig. 7 we show all the peak frequencies taken from data sets such as that shown in Fig. 6, obtained from three polycrystals. The data are plotted versus wall speed. At small speeds, the peak frequencies increase with $V_{\text{wall}}$. At higher speeds, the peak
Fig. 7  Peak frequencies of vibrations at 0.5 K versus wall speed. Various symbols denote data obtained from three different polycrystals. Dashed line is a guide to the eye. The error bars combine the width of each vibration peak (as in Fig. 6) and the uncertainty in determining the speed of the TO. The single point at the origin shows the measured uncertainty of the speed of the TO, not a vibration spectrum.

frequencies level off. In Fig. 8, we show the same data after averaging all the points taken with the same wall speed. Evidently, at small speeds the peak frequency increases linearly with $V_{\text{wall}}$. The lines in the figure show the $f-V_{\text{wall}}$ relation for the case where the friction is zero ($f = V_{\text{wall}}/d$). Taking the friction to be zero is consistent with the overall zero dissipation which we measured at 0.5 K. The two lines in Fig. 8 differ by the value of $d$, the distance between nearest rows of atoms. The value of $d$ which fits the data is for the surface of the moving solid being (0001), the basal plane of the hcp structure, with the in-plane direction of motion shown in the inset. This result suggests that under the shear stress applied by the TO, the crystalline grains near the wall reorient themselves with their (0001) planes parallel to the wall, so their $c$ axis is horizontal. This reorientation takes place during the relaxation process shown in Fig. 3.

Finally, we remark that (0001) is the only natural slip plane $[8,10]$ for hcp $^4$He.

It is interesting that we were able to observe well-defined vibrations only at 0.5 K, where the overall dissipation inside the solid tends to zero, but not at higher temperatures. One would think that with small enough friction it would still be possible to observe vibrations, perhaps at a lower frequency or weaker in intensity, but this was not the case. It may be that at temperatures above 0.5 K, where we detect a finite dissipation, the relative motion at the interface is not regular enough to produce vibration we can detect. This could happen for example if the friction at temperatures above 0.5 K is of the slip-stick type.

Referring again to Fig. 8, for $V_{\text{wall}} \geq 7 \mu \text{m/s}$, the peak frequency saturates at $\sim 60 \text{kHz}$. This leveling off suggests that the conditions of zero friction which account for the linear part no longer apply. However, well-defined vibrations are still observed.
Simulations done with two masses coupled by a frictional force proportional to velocity indicate that the frequency of vibrations, proportional to \((V_{\text{wall}} - V_{\text{solid}})\), should gradually decrease to zero as \(V_{\text{wall}}\) increases instead of staying constant. We also considered an alternate possibility, that the frequency in Fig. 8 saturates due to presence of defects at the interface which limit the amplitude of frictionless motion to some finite value. We assume that at higher amplitudes, the friction is finite. Calculations done with this scenario show that the peak frequency continues to change with wall speed, and does not saturate. Hence, those simple scenarios cannot explain the data.

One possibility of understanding the presence of a low friction state follows from the results of Path Integral Monte Carlo (PIMC) simulations of grain boundaries in hcp \(^4\)He by Pollet et al. [20]. Pollet, et al. showed that in equilibrium, the interfaces in most grain boundaries are fluid. The initial configuration of their simulation [20] is that of two solid grains of different orientations in contact along a GB. Once the simulation began, 2–3 atomic layers at the interface spontaneously became fluid. The reason for this is thermodynamic—the presence of fluid lowers the interfacial energy. In addition, the orientation of the GB spontaneously changed from the initial one. These authors were able to conclude that a fluid layer appears on most GB’s, but not on all of them. No less important, they found that the fluid layer is not an usual bulk liquid—it is metastable, in the sense that it appears only at a GB. These PIMC results were largely confirmed experimentally in inelastic neutron scattering on solid He contained inside a porous material [21]. This experiment [21] detected superfluid-like excitations inside the solid. In a porous material with a large surface area, the contribution of the He near surfaces to the scattering intensity is substantial, and so the experiment was able to detect them.
Microscopic theory calculations presented in the same paper show that the presence of a 1–2 atomic layers of superfluid at the interfaces would explain these results. In the present context, a fluid layer which spontaneously appears at the internal interfaces inside the TO would act as a natural lubricant which would allow the grains to "slide" against each other. Its spontaneous appearance at grain boundaries might explain why "mass decoupling" is observed as soon as the single crystal is disordered (Figs. 2, 3) and grain boundaries are created. Since the PIMC simulations show that the fluid is present at most GB’s, then the GB’s inside our TO would not have to be identically oriented around the circumference of the annular channel. Finally, these simulations [20] show that the grain boundaries become superfluid around 0.5K. This may be related to the observation that the measured internal dissipation of our TO goes to zero at 0.5 K.

In conclusion, we developed a new technique to characterize the interface between He crystallites as they move past each other. We confirmed that this relative motion indeed exists and the surface of the moving crystallites is the basal plane of the hcp structure. These findings are essential for future studies of friction. Our results are compatible with the notion that at small enough speeds, the motion of grains with the (0001) surface is frictionless at $T = 0.5$ K.

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**Appendix: Finite Element Analysis**

Clark et al.[16] were the first to point out that the resonance frequency of the TO can be affected by the changes of the shear modulus of the solid He. Specifically, they addressed the low-temperature anomalies reported by Kim and Chan[3] around 0.2K. The shear modulus of the solid changes significantly around this temperature[7]. Over the temperature range of our experiment (0.5–2K), the shear modulus changes by about 30%, as reported by Paalanen, et al.[11]. The shear modulus increases gradually towards low temperatures. To see how this affects our experiment, we performed a Finite Element Analysis of our TO. We simulated two different situations. First, we checked the decrease of the resonant period resulting from the increase of the shear modulus as the temperature is reduced from 2 to 0.5K. The simulated decrease in this case is about 7 nsec, while our observed decrease of the period (due to what we call "mass decoupling") is typically between 0.6 and 1 μsec, a hundred times larger. In addition, the elastic properties of the solid change smoothly as the temperature decreases from 2 to 0.5K, while in our experiment the majority of the period shift occurs over a 10 mK interval near the temperature at which the crystal was grown. We conclude that our observations cannot be explained by the temperature dependence of the shear modulus of solid He.

Another scenario which we checked in conjunction with the decrease of the resonant period which we see (Figs. 2, 3) is the following: Suppose that at the end of growth, a small amount of liquid remains trapped in the cell so that the solid is not fully coupled with the walls of the TO. Once the cell is cooled, this liquid freezes and the solid He becomes coupled to the walls. This coupling might perhaps make the TO "stiffer",
increase the effective torsion constant, and decrease the period. To check this scenario, we extended the finite element analysis to simulate the TO in several configurations where some fluid is present in the cell in different locations. To illustrate what we did, we show one such configuration in the Fig. 9. In this particular configuration the coupling of the solid He to the walls is minimal, and so the presence of the liquid had the largest effect. The simulated period of the TO was compared with that of a cell filled with solid. Since the amount of solid He (and moment of inertia) of the cell containing fluid is different than that of a cell filled with solid, for each configuration we carried out a series of FEA simulations with different amounts of liquid and extrapolated to zero liquid content. The extrapolated value was used in the comparison.

For the configuration shown in Fig. 9, in the limit of zero liquid content, the simulated period shift is (+)71 nsec. This should be compared to the observed shift of (−)0.6 to (−)1 µsec in different crystals and TOs. The difference in sign results from the fact that in the accelerated frame of the TO, a fictitious D'Alembert force acts on the solid He during the oscillation. Due to its small resistance to shear, in the presence of liquid the solid He is free to deform slightly under this force and so effectively it appears to oscillate in antiphase to the motion of the TO. This type of response increases the effective torsion constant and so the effective period is smaller. When the cell is filled with solid, this internal oscillation does not take place, the additional contribution of the solid He to the effective torsion constant is now smaller and so the period increases. This gives the (+) sign. In all cases, we found that the simulated period shift was of the opposite sign and at least an order of magnitude smaller than what we observed in the experiment. We conclude that the presence of liquid cannot explain our observations.

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