Observations on Non-Classical Behavior of Solid $^4$He with Compound Torsional Oscillator

M.C. Keiderling, Y. Aoki and H. Kojima
Serin Physics Laboratory, Rutgers University, Piscataway, New Jersey 08854 USA
E-mail: kojima@physics.rutgers.edu

Abstract. The response of oscillating hcp solid $^4$He samples was studied with a unique compound torsional oscillator a dummy mass and a sample (cylindrical or annular) container connected by two torsion rods. Identical solid sample could be probed within the same apparatus at two different frequencies ($\sim 0.5$ and $1.2$ kHz) separately or simultaneously. The apparent onset of the non-classical rotational inertia (NCRI) occurred at a higher temperature in the higher frequency mode. The peak in dissipation of the higher mode also occurred at higher temperature. Surprisingly, the mechanical dissipation was significantly greater in the lower mode. When the lower mode was driven at high levels to induce "critical state" in the sample and the higher mode was simultaneously driven at a low level for probing, the critical state seen in the lower mode did not entirely appear. Conversely, if a critical state was induced by the higher mode, it also did not appear in the lower mode. These preliminary results are contrary to the simple expectation from identifying the critical state as indication of suppressed superfluid density.

1. Introduction
The search for supersolidity, the unusual state of matter exhibiting the coexistence of superfluidity and crystallinity, was rekindled by the exciting discovery of decoupling of solid $^4$He from torsionally oscillating containers [1, 2]. The observed apparent partial decoupling between solid $^4$He sample and its container walls indicated superfluidity in the solid $^4$He. Thermodynamic signatures in the solid $^4$He heat capacity have been observed near the temperatures where the decoupling occurred. There have been conflicting observations on the flow of solid $^4$He depending on the design of the experiments [3–5]. There is as yet no generally accepted understanding of the observed phenomena [6, 7]. Some of the theoretical ideas contain predictions on frequency dependence of the magnitude of decoupling. Although the frequency of torsional oscillators varied between 180 and 1500 Hz, the oscillators contained independently grown solid $^4$He samples in different cells and laboratories. We report here on our measurements of NCRI of the identical solid $^4$He sample contained in a cylinder and an annulus attached to a torsional oscillator having two resonant frequencies differing by a factor of 2.4. We observe that the NCRI fraction and the associated dissipation depend on the cell geometry, the oscillation frequency, temperature ($T$) and the imposed oscillation velocity. In addition to these frequency dependent effects, we show clear evidence for hysteretic behavior of NCRI phenomenon depending on the history of oscillation velocity and thermal processing from the normal state above 300 mK to low temperature. An advantage of the compound oscillator is that both modes can be excited independently or simultaneously.

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2. Compound Torsional Oscillator and Procedure

Our compound torsional oscillator is analogous to the system of two masses attached to each other by two springs of which one is attached to an isolator block of large mass. One mass was a “dummy” block of BeCu and the other mass contained either cylindrical (10 mm diameter and 8 mm height) or annular (10 mm outer diameter, 8 mm inner diameter and 8 mm height) sample cell. The torsion rods were made of BeCu of 2 mm diameter and 12 mm length. The frequencies \( f_1 \) and \( f_2 \) of the lower (the mass motion in phase) and higher (out of phase) were 490 and 1172 Hz. The measured frequencies were close to those estimated from the moments of inertia of the parts and the torsion constant of the BeCu rods. The quality factors \( Q_{1b} \) and \( Q_{2b} \) of the modes 1 K were 1.3\times10^6 and 7\times10^5 for \( f_1 \) and \( f_2 \) modes, respectively. The copper isolator block was rigidly attached to the mixing chamber of a dilution refrigerator. The temperature of the modes due to loading near 300 mK were approximately \( \Delta f_1 = 0.667 \pm 0.40 \) Hz, and \( \Delta f_2 = 2.049 \pm 1.28 \) Hz in the cylindrical (annular) cell. Further decreases \( \delta f_1 \) and \( \delta f_2 \) in frequencies below 300 mK and the quality factors \( Q_{1b} \) and \( Q_{2b} \) were measured as the temperature was varied. This shows both the NCRIf and the dissipation of the two modes measured in this manner. The dissipation peak of the \( f_2 \) mode is greater than that from \( f_1 \) mode. The difference in the temperature at the dissipation peaks is 10 mK for \( f_2 \) mode at \( T < 100 \) mK and 30 mK for \( f_1 \) mode. The temperature of the sample was intentionally kept below 300 mK to avoid introducing any annealing effects. Our conclusion is that the rim velocity still best describes the reduction of NCRIf measured from the two modes. 

3. Results

We reported previously on our experiment addressing the question of which amplitude controlled the reduction of NCRIf in the cylindrical sample [8]. It was concluded that the reduction extracted from the two modes was best described by the amplitude of the sample rim velocity. Since that report appeared, the calibration of the cell rim motion in terms of the motion of the detector electrodes mounted on the dummy mass were repeated and reevaluated. Corrected comparison of NCRIf as functions of the displacement, velocity and acceleration at the sample rim is described in Fig. 1. Our conclusion is that the rim velocity still best describes the reduction of NCRIf measured from the two modes.

To study the effect of frequency on the response of the solid \(^4\)He sample contained in the annular cell, both modes were driven and tracked simultaneously as the temperature was varied. The drive levels were kept low (9–16 and 4–15 \( \mu \)m/s for \( f_1 \) and \( f_2 \) modes, respectively) at all temperatures such that critical velocity effects on the \( \delta f \) shifts were minimal. The simultaneous tracking ensured that both modes were measured at the identical sample temperature. Fig. 2 shows both the NCRIf and the dissipation of the two modes measured in this manner. The NCRIf derived from the \( f_2 \) mode is greater than that from \( f_1 \) mode at all temperatures. This is in contrast with the cylindrical sample [8] in which both \( f_1 \) and \( f_2 \) modes showed the same NCRIf below 40 mK. The dissipation peak of the \( f_2 \) mode occurs at the temperature 10 mK warmer than that of the \( f_1 \) mode. The difference in the temperature at the dissipation peaks is greater in the annular than in the cylindrical sample.

The compound oscillators allows detecting NCRIf with one mode driven at sufficiently low
Figure 1. NCRI fractions evaluated from the frequency shifts in the first (crosses) and second (triangles) mode as functions of displacement ($d$, top panel), velocity ($v$, middle) and acceleration ($a$, bottom) of a 37 bar cylindrical solid $^4$He sample at 19 mK [8]. The displacement, velocity and acceleration are based on the most recent calibration of the detector motion. For comparison, the values of $d$, $v$ or $a$ for each mode at NCRIf = 0.05 % are read from the plots. Evaluating $|y_1 - y_2|/y_1$ gives 0.7, 0.3 and 0.6 for $y = d$, $v$ and $a$, respectively. The best match is given by the dependence of velocity, but the match is not as precise as shown in our previous report.

Figure 2. Temperature dependence of NCRI fraction (left scale) and dissipation (right scale) measured by simultaneous tracking both $f_1$ (thin lines) and $f_2$ (thick lines) modes in annular solid $^4$He sample at 42 bar. Both modes were driven at low drive levels starting at high temperature and measured during cool down such that there is little suppression of supersolid signal. The magnitude of NCRIf in the annular sample was increased by more than two-fold from those in our [9] cylindrical samples. The peak in $\delta Q_{f_1}^{-1}$ occurs at about 10 mK above that of $\delta Q_{f_1}^{-1}$.

level (which, on its own, would not take the sample into a critical state) while the drive level of the other mode is varied such that the sample is driven deep into the critical region. Naively, we would expect NCRIf measured by both modes to be same. Fig. 3 shows an example such a study. The suppression of NCRIf derived from $f_1$ was as expected [8] from it being driven alone as the drive level was decreased to the minimum in Fig. 3. However, the suppression seen by $f_2$ was not as large in the same process. When the $f_1$ drive level was increased back up from the minimum, the NCRIf remained constant in both modes. Preliminary analysis shows that, if the roles of $f_1$ and $f_2$ modes in the above process are reversed, NCRIf sensed by $f_2$ is suppressed more than that by $f_1$. 

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Figure 3. NCRIf of annular sample measured by $f_1$ (crosses) and $f_2$ (triangles) modes while changing the drive level (converted to rim velocity amplitude by $\sim 0.9 \mu m/s/mV$) of $f_1$ mode. Beginning near 280 mK, the drive level of the $f_1$ mode was increased to 700 mV and that of the $f_2$ mode was set to a low level. The system was then cooled down to 9.7 mK while driven simultaneously at the respective levels. Subsequently, both modes were tracked when the $f_1$ drive level was varied as shown by arrows while keeping the $f_2$ drive level constant at the low level.

4. Discussions and Conclusions
The dependence of the suppression of the NCRI fraction in the cylindrical sample in our compound oscillator is best described in terms of the rim velocity rather than displacement or acceleration. The hysteresis of NCRI during reversals of rim velocity, originally reported by us in the cylindrical sample [8], was observed in an annular 1 mm wide sample. The details of the hysteresis appears to depend on the width or possibly the surface to volume ratio of the sample [10]. The naive expectation that the NCRI suppression being determined by the larger drive mode in our compound oscillator was not totally in accord with simultaneous drive experiments. The temperatures at which the dissipation peaks occur were more widely separated in our annular than cylindrical sample. According to the Anderson vortex liquid model [11] of NCRI phenomena, the dissipation peak occurs when the frequency of vortex motion in and out of the sample matches the oscillator frequency. If the model is applicable, experiments indicate that the vortex motion frequency is smaller in our annular than in cylindrical samples at a given temperature.

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