We have used a torsional oscillator with square cross section and a resonance frequency of 185 Hz to confirm the nonclassical rotational inertia (NCRI) discovered by Kim and Chan\cite{1,2}. We have also found a strong correlation between the NCRI signal and a high dissipation $Q^{-1}$ of $4 \times 10^{-6}$ of the oscillation above the transition temperature. Here, we present preliminary results of the annealing process in $^{4}\text{He}$ at a pressure of 26 bar. When holding the temperature constant above 1 K we have observed an immediate rise in the period and a slow decay of the dissipation. The equilibrium value of $Q^{-1}$ decreases with increasing temperature.

PACS numbers: 67.80.-s, 67.80.Mg

1. Introduction

Eunseong Kim and Moses Chan (KC) of Penn State University first observed\cite{2} nonclassical rotational inertia in solid $^{4}\text{He}$ (NCRI) below 250 mK. As previously reported\cite{4}, we were able to confirm NCRI in bulk solid. More importantly, we also observed classical rotational inertia in the same cell by annealing the sample and by raising the pressure above 32 bar.

All crystals in the NCRI state had a dissipation $Q^{-1}$ above $4 \times 10^{-6}$ at 300 mK. The classical rotational inertia state (CRI) was characterized by a relatively low dissipation of $1 \times 10^{-6}$, comparable to the empty cell dissipation. We believe that this low dissipation could indicate a state with less defects than in the supersolid samples. This observation suggests that crystal imperfections like grain boundaries or point defects are probably essential for the existence of the supersolid state.
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Fig. 1. Torsional oscillator: The torsion cell’s motion is excited and detected capacitively. The AC voltage on the detection electrodes serves as reference signal for a lock-in amplifier to keep the oscillation in resonance. At 4 K, the mechanical quality factor is $9 \times 10^5$, and the resonance frequency is 185 Hz.

2. Experimental Setup

A schematic view of the oscillator is shown in Fig. 1. We used an oscillator with a volume of 1.4 cm$^3$, operated at 185 Hz. The scale for the dissipation $Q^{-1}$ is determined by a ring-down measurement of $Q$ at the base temperature of 20 mK. The empty cell value at 1 K is $1.0 \times 10^{-6}$. 

The interior of the cell is a nearly cubic geometry which was obtained by epoxying a Tellurium-Copper insert into the cylindrical volume of the Beryllium-Copper oscillator. When cooling down, the solid samples were grown with the blocked capillary method such that the helium crystal was formed in the fill line first. The helium used in the experiments had a nominal $^3$He concentration of 0.2 - 0.3 ppm. The pressure of the solid samples, discussed here, was 26 bar.

3. Experimental observations

After forming the solid sample, we cooled it down to 20 mK. Below 250 mK, we observed that the period gradually falls below the empty cell value with the biggest change below 200 mK. Below 100 mK, the period levels off. The total period drop is 80 ns, which compares to the NCRI that KC as well as Motoshi Kondi and Keiya Shirahama observe. Period and
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Fig. 2. The resonant period while warming up (closed circles) and cooling down (open circles) is shown as a function of temperature for a sample at 26 bar. The data was taken while warming up slowly after a cool-down that showed NCRI with a period drop of 80 ns. The maximum wall velocity is 80 $\mu$m/s.

dissipation signals for a typical cooldown at this pressure and velocity are shown elsewhere.\[4\]

Afterwards, we warmed up very slowly such that the sample was held between 1.0 K and 1.3 K for 16 hours. The period and dissipation (both filled circles) $Q^{-1}$ as a function of temperature are shown in Fig. 2.\[4\] At temperatures above 0.8 K, the period rises steeply by 100 ns until it levels off at about 1.2 K. In the same temperature interval, the dissipation decays from $16 \times 10^{-6}$ (at 0.7 K) to $2 \times 10^{-6}$ (at 1.3 K). This contrasts the behavior between 0.3 K and 0.8 K where we have observed no sudden changes in either P or $Q^{-1}$. Since the warm-up was very slow, we believe that the period and dissipation were in thermal equilibrium.

After having held the temperature between 1.2 K and 1.3 K for nearly 12 hours, we lowered the temperature again below 1 K. The period and dissipation (open circles) of this cool-down are also shown in Fig. 2.\[4\] When the temperature is lowered the curves do not reverse. Instead, the period drop is reduced to 10 ns and the dissipation exhibits only a small drop to $3 \times 10^{-6}$ at 0.7 K. We cooled down through the supersolid transition and observed a greatly decreased period drop of 7 ns at 170 mK. This is the
Fig. 3. The dissipation while warming up (closed circles) and cooling down (open circles) is shown as a function of temperature for a sample at 26 bar. The data was taken while warming up after a cool-down that showed NCRI and $Q^{-1}[300 \text{ mK}]$ of $16 \times 10^{-6}$. The maximum wall velocity is $80 \mu\text{m/s}$.

"partially annealed" NCRI as reported earlier[4].

Another sample that showed NCRI at low temperatures was warmed up quickly to 1 K. Between 250 mK and 900 mK the dissipation was of the order of $10 \times 10^{-6}$ without any sudden changes and the period increased only gradually. We also observed a gradual increase of the empty cell period when warming. After reaching 1 K, we warmed up in steps, holding the temperature for about an hour each at 1 K, 1.2 K and 1.44 K. The melting temperature of $^4\text{He}$ at 26 bar is 1.5 K. In Fig. 4 we show an example of dissipation and period versus time at a temperature of 1.2 K. When the temperature is held constant, the period rises immediately (not shown in Fig. 4) whereas the dissipation decays slowly to an equilibrium value $Q_0^{-1}$. We fit the data to an exponential decay and obtain a time constant of about 8 minutes. This time constant is similar for the three temperatures. With increasing temperature, the period increases which confirms the temperature dependence observed in the sweep (Fig. 2). The dissipation drops from $8.6 \times 10^{-6}$ (1 K) to $2.9 \times 10^{-6}$ (1.2 K) and finally $2.5 \times 10^{-6}$ (1.44 K). The period rises from 5.428310 ms (1 K) by 27 ns (1.2 K) and 45 ns (1.44 K) respectively. The equilibrium values for period and dissipation match the ones found in Fig. 2.
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Fig. 4. The dissipation data (circles) and resonant period (stars) are shown as a function of time at 1.2 K. The data was taken after a cool-down with a period drop of 50 ns at a pressure of 26 bar. The period is shifted by $P^*$ ($= 5.428337$ ms), the resonant period at 1.2 K. The dissipation data is fit exponentially (red line) and yields a time constant of 8 minutes.

4. Discussion

We find that the NCRI is associated with a state of high dissipation, $Q^{-1}$, for the $^4$He solid which may be caused by defects in the crystal. The absence of supersolid behavior in the annealed samples is supported by the recent theoretical findings that an ideal hcp $^4$He crystal does not support ODLRO or BEC\cite{56}. When we warm up and anneal the sample the dissipation decays to almost the empty cell value of $1.0 \times 10^{-6}$. One may explain this drop with defects or dislocations leaving the crystal.

KC and Shirahama have also undertaken annealing experiments\cite{37}, but have not been able to eliminate their NCRI signals. We note that there are differences in geometry, pressure and frequency between the experiments. At the moment, we do not know how the experimental differences contribute to crystal quality and to successful annealing.

We also find that the dissipation does not decay to its lowest value of about $1 \times 10^{-6}$ at temperatures at and below 1.44 K. Instead, the equilibrium value for the dissipation is temperature dependent such that higher temperatures are needed in order to completely remove the NCRI signal.
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ACKNOWLEDGMENTS

The work reported here has been supported by the National Science Foundation under Grant DMR-060584 and through the Cornell Center for Materials Research under Grant DMR-0520404.

REFERENCES

1. E. Kim and M. H. W. Chan, *Nature* **427**, 225 (2004).
2. E. Kim and M. H. W. Chan, *Science* **305**, 1941 (2004).
3. M. Kondo, S. Takada, Y. Shibayama and K. Shirahama *cond-mat/ 0607032* (2006)
4. A. S. C. Rittner and J. D. Reppy, *Phys. Rev. Lett.* **97** 165301 (2006).
5. B. K. Clark and D. M. Ceperley, *Phys. Rev. Lett.* **93** 155303 (2004).
6. M. Boninsegni, N. Prokof’ev and B. Svistunov, *Phys. Rev. Lett.* **96** 105301 (2006).
7. E. Kim and M. H. W. Chan *Phys. Rev. Lett.* **97** 115302 (2006)