Supersolid ^{4}He under DC rotation: energy dissipation for slow and fast temperature sweeps

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Abstract. In this report, we describe torsional oscillator (TO) measurements under DC rotation of a 49 bar ^{4}He-sample, at $V_{ac} = 0.2$ mm/s. We investigated the behavior of the energy dissipation ($\sim \Delta Q^{-1}$) as well as the supersolid fraction for different rotation velocities ($0 < \Omega < 1.256$ rad/s) and $V_{ac} = 0.06$, 0.2 mm/s in the temperature range of from 47 mK to 150 mK, using fast ($\sim$3h) and slow ($\sim$55h) temperature sweeps. Variation of Ω did not influence the supersolid fraction. The performed analyzes have shown a linear increase of the ΔQ^{-1} vs. Ω for high $V_{ac} = 0.2$ mm/s (for fast and slow temperature sweeps). In the case of $V_{ac} = 0.06$ mm/s, no change of the energy dissipation was observed up to $\Omega = 0.628$ rad/s for the low temperature limit. These results suggest a possible explanation for the energy dissipation in supersolid ^{4}He and its proportionality to the number of low dimensional vortices influenced by torsional oscillations. The 3D-vortex lines created by DC rotation can dissipate their energy by interaction with low dimensional vortices. Their dynamics under rotation are characterized by long relaxation times.

1. Introduction

It was proposed in 1969-70 that a quantum crystal, where atoms undergoing large quantum fluctuations around the lattice sites, could manifest supersolid behavior [1, 2, 3]. Despite a number of experimental attempts, a supersolid [3] has not been observed [4] until the recent study of solid helium confined in porous Vycor glass [5]. In these experiments the resonant period and the amplitude of a high-Q torsional oscillator (TO) filled with solid helium was measured. This observation has been continued by several other torsional oscillator experiments and new interesting features were found [6, 7, 8, 9, 10]. Although the temperature dependence of the NCRI fraction (NCRIF) is entirely reproducible, its magnitude ranges from 0.015% up to 20% in quench-cooled samples of solid ^{4}He in the form of very narrow annuli [11]. This suggests that defects inside crystalline ^{4}He could have a great impact on the supersolid phenomenon. Another important condition which can influence the supersolid behavior and thus the amount of NCRIF is the concentration of ^{3}He impurities.

In our recent report [12], we describe torsional oscillator (TO) measurements under DC rotation of a 49 bar ^{4}He-sample, at $V_{ac} = 0.2$ mm/s for a fast ($\sim$3h) temperature sweep. We also investigated the behavior of the energy dissipation (ΔQ^{-1}) as well as the supersolid fraction for different rotation velocities ($0 < \Omega < 1.256$ rad/s) and $V_{ac} = 0.06$, 0.2 mm/s in the temperature range of from 47 mK to 150 mK, using slow (∼3h) and fast (∼55h) temperature sweeps.

Our observation can be explained by vortex fluid state which appears below T_0 but above T_c [17, 10]. A real supersolid as it was proposed by P.W. Anderson [17] occurs below T_c where one can expect an extra energy dissipation as it was observed for 3D-connected KT-films under DC rotation [18, 19].

2. Experimental methods

This experiment requires not only an extremely stable rotating cryostat but also an adequately high-Q torsional oscillator containing a carefully prepared solid ^{4}He sample. We were able to perform our measurements using a single sample which remained highly reproducible throughout six months of experiments.

The NCRI fraction response can be determined by reduction in resonant period of a TO filled with solid ^{4}He and comparison to an empty TO divided by f_{load} (change of the resonant period due to the solid sample) [10]. The torsional oscillator used in the measurements has a 15 mm long torsion rod with 2.2 mm outside diameter and a 0.8 mm coaxial hole serving as the filling line. It was mounted to a dilution refrigerator placed on an air bearing supported by a stainless steel frame. The whole system provides excellent vibration isolation thus decoupling from external influences. The cylindrical bob is made of brass and is mounted on a BeCu base integral with the torsion rod. The interior sample space is 4 mm high and has 10 mm diameter. Below 4.2 K the resonant frequency of the TO is approximately 1 kHz with a quality factor, Q $\sim 1.7{*}10^6$, as determined from the free decay time constant. Although the system is capable of rotation as fast as ∼6.28 rad/s, reliable data could only be obtained up to 1.256 rad/s. Above this Ω the instability of the TO became excessive. The solid sample was prepared by the blocked capillary method from ^{4}He gas of commercial purity (∼0.3 p.p.m. ^{3}He), with cooling along the melting curve at a rate of ∼2 mK/min. The final pressure of the solid was estimated from a sharp drop in TO amplitude at the melting temperature measured during slow (∼0.5 mK/min) heating after completion of the measurements [9]. Our data sets for period and amplitude were obtained during slow (∼0.4 mK/min) and fast (∼1 mK/min) warming sweeps.

3. Results

All the period and amplitude data were obtained during warming scans after waiting for complete equilibration at the lowest temperature. The top graphs (A) in all figures show the inverse quality factor of the TO (ΔQ^{-1}), which is proportional to the energy dissipation in the solid ^{4}He, $\delta \sim \Delta\, Q^{-1}$, while the bottom graphs (B) illustrate the relative shift of the period, $\Delta p/\Delta p$load corresponding to the NCRIF of the solid ^{4}He as a function of T for two V_{ac} = 0.06, 0.2 mm/s and DC velocities in the range of from 0 to 1.256 rad/s.

For the fast temperature sweeps (figures 1 and 3) additional dissipation below the energy dissipation peak (T_p), ∼85 mK, can be observed. They show a linear increase with increasing Ω up to 1.256 rad/s. For larger Ω, this effect could not be observed, since instabilities of the TO caused by faster rotation prevented recording reliable data. In case of the slow temperature sweeps (figures 2 and 4) the extra energy dissipation is even more pronounced. Furthermore the center of the energy dissipation peak shifts towards lower temperature, reaching ∼75 mK. This temperature corresponds to the center of the specific heat peak [13] (for the same amount of ^{3}He impurities, 0.3 p.p.m.).

Another important observation related to all bottom figures (B) is that the period shows no significant variation with DC velocity (Ω) within the experimental error. This indicates that the additional dissipation process occurs only within the supersolid phase.

It has been reported that DC rotation is the most straightforward way to excite 3D-quantized vortices in bulk superfluid ^{4}He [14, 15]. The rotation-induced vortices can contribute to the

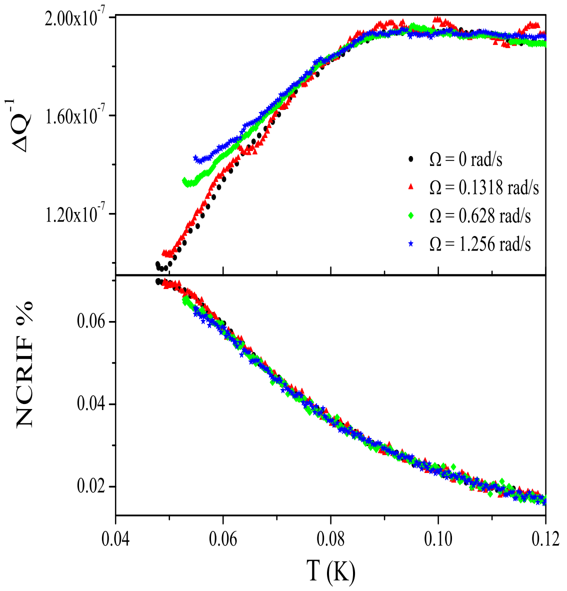

Figure 1. Temperature dependence of NCRIF and energy dissipation ΔQ^{-1} under DC rotation for the 49 bar sample. All data were measured for the same V_{ac} = 0.06 mm/s during ~3h temperature sweep.

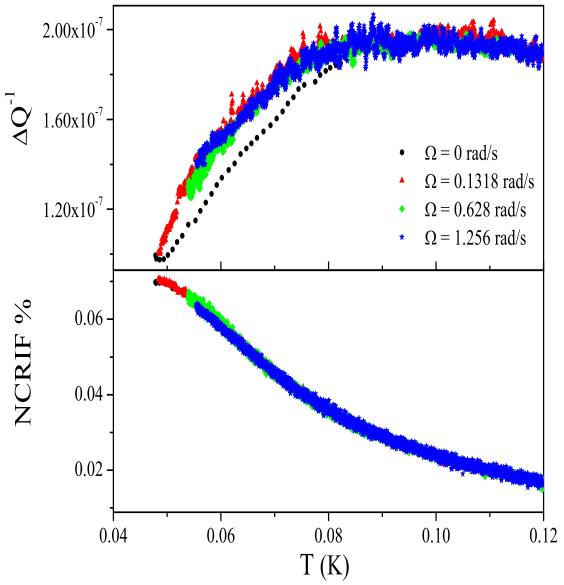

Figure 2. Temperature dependence of NCRIF and energy dissipation ΔQ^{-1} under DC rotation for the 49 bar sample. All data were measured for the same V_{ac} = 0.06 mm/s during ~55h temperature sweep.

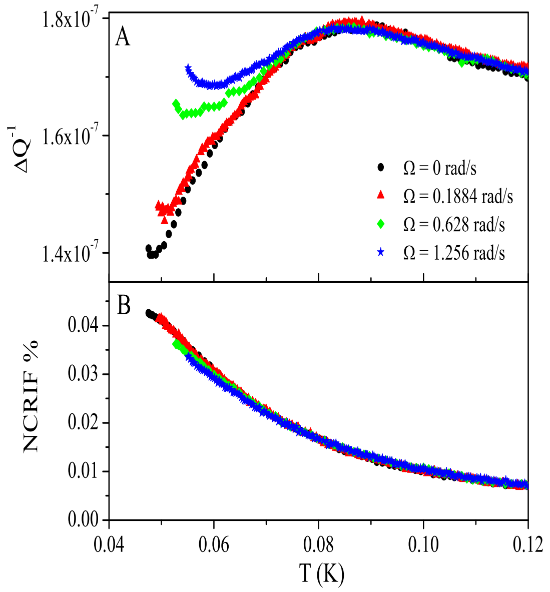

Figure 3. Temperature dependence of NCRIF and energy dissipation ΔQ^{-1} under DC rotation for the 49 bar sample. All data were measured for the same V_{ac} = 0.2 mm/s during ~3h temperature sweep.

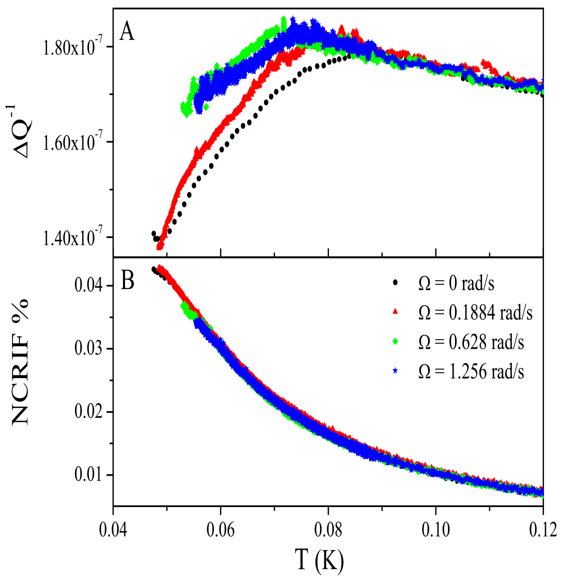

Figure 4. Temperature dependence of NCRIF and energy dissipation ΔQ^{-1} under DC rotation for the 49 bar sample. All data were measured for the same V_{ac} = 0.2 mm/s during ~55h temperature sweep.

energy dissipation [16, 17]. One possible mechanism of the extra energy dissipation, so called "phase slippage" involves the change of the phase of the 3D-vortex as it crosses another "object" (3D-vortex or low D vortex) was proposed by P.W. Anderson. TO experiments on ^{4}He films adsorbed on porous media under rotation have revealed the extra energy dissipation where the "pore vortices" were induced by DC rotation and their energy was disspated due to the interactions with the pore walls.

Our observation of the additional energy dissipation in solid ^{4}He not only proves the existence of 3D-coherent, DC induced vortices but also indicates that their dynamic behavior is characterized by long relaxation times. The extra ΔQ^{-1} appears below the center of the energy dissipation peak which also shifts depending on duration of the temperature sweep: ∼85 mK for the ∼3h sweep and ∼75 mK for the ∼55h sweep. Most likely the increase in the ΔQ^{-1} is caused by interaction of the low-D, thermal vortices with the macroscopic 3D-lines and the long relaxation time may indicate a turbulent dynamics.

Our results, in particular in combination with those of heat capacity measurements[13], indicate that solid ^{4}He can undergo a phase transition from a vortex fluid state composed of low-dimensional, thermally excited vortices, into a 3D-coherent state, the supersolid. The microscopic process causing such behavior is not yet understood in detail, but a clearer picture is emerging.

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