Low Frequency Shear Modulus of bcc $^3$He Below 1 K

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Abstract. Recent measurements on hcp $^4$He crystals showed an anomalous stiffening of the shear modulus below 200 mK. This is the temperature range in which torsional oscillator experiments saw evidence of supersolidity. The temperature, frequency, strain amplitude and $^3$He impurity dependence of the shear modulus mirrored that of the torsional oscillator period, indicating that they are closely connected, although the exact relationship is not clear. The elastic behavior appears to be related to the mobility and impurity pinning of dislocations. Since the behavior of dislocations depends on crystal structure, while supersolidity is not expected in solid $^3$He, we have extended our shear modulus measurements to the bcc phase of high isotopic purity $^4$He (1 ppm $^4$He). We do not see a modulus anomaly like that in hcp $^4$He, nor is there significant amplitude dependence. We compare the behavior of hcp $^4$He to that of bcc $^3$He. Measurements on high purity hcp $^3$He will provide the most valuable comparison to the supersolid $^4$He system.

1. Introduction

The discovery [1] of decoupling in torsional oscillator (TO) measurements, and its interpretation in terms of “non-classical rotational inertia” (NCRI) and supersolidity, generated a great deal of interest in other properties of solid helium. In recent measurements of the low frequency shear modulus ($\mu$) of hcp $^4$He, we observed [2] a large and unexpected stiffening at low temperatures. Its temperature, frequency, amplitude, $^3$He impurity and annealing dependences were essentially the same as those of the NCRI. However, the elastic anomaly appeared to be related to the motion of dislocations and their pinning by $^3$He impurities. Given the apparent close connection between $\mu$ and the NCRI, it is important to see how the shear modulus depends on statistics ($^4$He vs. $^3$He) and on crystal structure (hcp vs. bcc). In this paper, we present measurements of the shear modulus of bcc $^3$He.

2. Experimental details

Our measurements were made in a copper cell mounted on the mixing chamber of a dilution refrigerator. A 0.004” i.d. CuNi capillary, thermally anchored at the 1 K pot and to the refrigerator’s heat exchangers, was used to introduce $^4$He and $^3$He to the cell. The crystals were grown using a standard blocked capillary method. The $^4$He gas used in our experiments ranged in isotopic purity from ~ 0.3 ppm $^3$He down to 1 ppb $^3$He. The bcc $^3$He crystals were grown from gas with 1 ppm $^4$He. Temperature was measured with a calibrated germanium thermometer above about 50 mK, with a
Co nuclear orientation thermometer for lower temperatures. The cell included an in situ Straty-Adams capacitive pressure gauge with a resolution and stability better than 0.2 mbar.

Elastic displacements were generated and stresses were detected by two parallel-aligned shear transducers in our cell. The transducers were epoxied onto solid brass backing pieces, which were themselves rigidly mounted onto a brass bar, ensuring that the faces between the transducers were parallel. The transducers were made from PZT 5A material (fundamental resonance at 500 kHz, with width W = 9.6 mm, length L = 12.8 mm, thickness t = 2.1 mm). For most of the $^4$He measurements we used a cell with an open volume of 25 cm$^3$ and a gap between transducers faces D = 180 µm. To grow $^3$He crystals, we reduced the volume to 4.5 cm$^3$ and also changed the gap to 500 µm.

A voltage V applied to the driving transducer produces a proportional shear displacement $\delta x$ at its front face. Sinusoidal voltages (frequency f) were generated using a synthesized function generator (Stanford Research Systems DS345). The 150 mVpp output was reduced by attenuators then directly measured using a digital multi-meter (Keithley 197) or an oscilloscope (Tektronix TDS2014B), so that the shear strain could be calculated for the helium in the gap ($\varepsilon = \delta x/D$). The resulting shear stress $\sigma$ produces a charge on the second transducer. This sent to an ultra-low-noise current preamplifier (Femto LCA 20K-200M) with a 14 fA/pHz equivalent input noise current, a 20 kHz bandwidth, and a gain of 2 x 10$^8$ V/A. The amplified current (I) was then detected with a 2-phase digital lock-in amplifier (Stanford Research System SR830 DSP), allowing background and electrical crosstalk signals to be subtracted even if they had different phases. The minimum detectable stress at 2000 Hz, set by noise in our preamplifier ($\approx$2.5 fA for 30 s averaging), is $\sigma \sim 10^{-5}$ Pa (which corresponds to a displacement $\delta x \sim 2 \times 10^{-16}$ m and strain $\varepsilon \sim 10^{-12}$). The shear modulus of the solid helium in the gap is $\mu = \sigma/\varepsilon$, which is proportional to I/f.

3. Results and discussion

In Figure 1 we compare the behavior of hcp $^4$He to that of bcc $^3$He. The various curves have been shifted vertically to display them on the same graph, but have the same scale, i.e. fractional as opposed to absolute modulus change. The top set of 3 curves is for hcp $^4$He - two samples with the normal 300 ppb $^3$He concentration and one isotopically pure (1 ppb $^3$He) crystal. The curves show the typical variation in the size of the low temperature shear modulus anomaly (about a factor of 2). The

![Figure 1: Temperature dependence of hcp $^4$He and bcc $^3$He shear modulus.](image)
lowest of these curves shows the shift of the anomaly’s onset to lower temperature in isotopically pure samples. The bottom two curves are for bcc $^3$He crystals grown at different pressures (55 and 83 bar). The behavior is quite different from that of hcp $^4$He, with no anomalous stiffening at low temperatures.

Figure 2 shows the shear modulus at different strains. For hcp $^4$He, $\mu$ is independent of drive amplitude for strains up to $\varepsilon = 2.2 \times 10^{-8}$ and then begins to decrease (much as the NCRI decreases as high TO amplitudes). The bcc $^3$He curves do not show any systematic amplitude dependence over the same range. Similar behavior was seen in the second bcc $^3$He crystal whose amplitude dependence we measured.

We also studied how the shear modulus is affected by annealing, which is expected to reduce the number of defects and change the dislocation network. As shown in Figure 3, the size of the low temperature anomaly in hcp $^4$He crystals is changed by annealing. It is the high temperature modulus which changes – the low temperature value of $\mu$ is unchanged, reflecting the intrinsic modulus of the

Figure 2. Strain amplitude dependence of of hcp $^4$He and bcc $^3$He shear modulus.

Figure 3. Temperature dependence of hcp $^4$He and bcc $^3$He shear modulus before and after annealing.
solid when dislocations are completely pinned by $^3$He impurities. Above about 100 mK, the $^3$He atoms thermally unbind allowing them to move and reducing the solid’s shear modulus. The bcc $^3$He crystals do not behave in the same way. As shown in Figure 3, annealing did not change the high temperature behaviour, but reduced the temperature dependence at low T. Other bcc $^3$He crystals had slightly different annealing behaviours, but never like that seen in hcp $^4$He crystals. Instead of a low temperature anomaly which decreases upon annealing, bcc crystals have a more significant background temperature dependence, but it varies from crystal to crystal and annealing does not change it in a systematic way.

The differences between the elastic behavior of hcp $^4$He and bcc $^3$He are consistent with a dislocation origin, since dislocation structure and mobility depend strongly on crystal structure. In hcp $^4$He and $^3$He, edge dislocations glide freely in the basal plane [3, 4], thus reducing the shear modulus by as much as 30% [5], but in most bcc crystals dislocations have to overcome a significant potential barrier in order to move. It is also consistent with the absence of any NCRI in TO measurements on bcc $^3$He [6]. It leaves open the very interesting question of hcp $^3$He, where dislocations and elastic behavior might behave as in hcp $^4$He, but supersolidity and NCRI are not expected.

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