Pressure relaxations in solid helium-4

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Abstract. Recently, we have used a torsional oscillator to observe supersolid fractions up to 20 % in confined helium samples. To characterize these constrained samples further we measure the solid pressure in a narrow pancake cell. We can fit the pressure data well to the functional form $p = p_0 + aT^2 + bT^4$. The term proportional to the temperature square indicates that crystalline disorder exists in the solid samples. The disorder term in the pressure can be reduced by sample annealing, i.e. holding the sample at a temperature close to the melting temperature. Secondly, when we hold the temperature fixed for an extended period of time, the pressure relaxes in a way similar to an exponential decay. The characteristic time constant of decay rises at low temperatures. The low temperature relaxations also reduce the disorder term in the pressure equation.

In torsional oscillator experiments the rotational inertia of solid helium drops abruptly below 200 mK [1, 2]. This nonclassical drop in the solid moment of inertia suggests that a phase exists with resistance to shear and frictionless flow. At this time, several laboratories have replicated the original experiments [3, 4, 5]. The dependence of signal size on helium-3 dependence [2], growth conditions [4], and sample geometry [6] is evidence that crystalline defects are essential for the anomaly. In particular, samples confined to thin annular geometries exhibit supersolid fractions up to 20 %. In the measurements reported here, we measure the solid pressure of confined helium samples. We find that these sample are highly disordered and that annealing can only remove some of the defects. Moreover, we observe relaxations of the sample pressure when we hold the temperature fixed at all temperatures. We attribute the relaxations to mass flow within the solid.

In our setup, the helium sample is constrained in a BeCu cylindrical pancake cell (height $h \approx 100 \mu m$, radius $r = 0.86 \text{ cm}$, volume $V \approx 0.023 \text{ cm}^3$, surface to volume ratio $S/V \approx 200 \text{ cm}^{-1}$). One end of the cylinder is a flexible diaphragm on which a Straty-Adams capacitance gauge is mounted. The resolution of the pressure gauge is on the order of 5 $\mu\text{bar}$. The confinement of the helium is 15 times smaller than in earlier pressure measurements [7].

The pressure, $p$, in disordered helium samples has four contributions [7]:

$$p(T) = p_0 + p_{\text{phon}} + p_{\text{dis}} + p_{\text{vac}}. \quad (1)$$

Here, $p_0$ is the pressure at zero temperature, $p_{\text{phon}}$ is the contribution from phonons, $p_{\text{vac}}$ stems from point defects, and $p_{\text{dis}}$ stems from crystalline disorder as grain boundaries [8], dislocations [9] or glassy regions [9]. The phonon contribution, $p_{\text{phon}}$, is proportional to the fourth power in temperature. Defects contribute to the pressure proportional to the square of temperature.
Figure 1. Two different thermal histories of helium samples. Left: the sample pressure is displayed as a function of cell temperature during blocked capillary growth. During solidification, the pressure drops from 67 bar to the final solid pressure of 42.1 bar. This sample took 106 minutes from the start of solidification until it was cooled below 1 K, solidification required 40 minutes. Right: pressure and temperature are shown as a function of time during a quench-cool. A heat pulse warms the sample rapidly and melts completely as can be seen from the maximum pressure at 70 bar. This sample then solidifies and cools below 1 K in 144 s.

Fig. 1 displays constant volume or blocked capillary (bc) growth and a rapid quench cool (qc). To determine the solid pressure, the pressure gauge is calibrated when the cell is filled with liquid helium. In the bc sample (left), it took 106 minutes to cool the sample below 1 K. Since quenching proved very successful in increasing supersolid signal sizes in torsional oscillators, we quenched the samples for pressure measurements as well. At the right of Fig. 1, temperature and pressure are plotted versus time during a quench cool. The qc technique reduced the time to refreeze and cool below 1 K to 144 s.

The left side of Fig. 2 shows the pressure of the same bc sample below 500 mK together with several different fits. The data cannot be fitted well to a Debye crystal with the pressure changing proportional to $T^4$ (green and blue solid lines). Instead, we obtain the best fit by fitting the data in the following form (red solid line):

$$ p = p_0 + aT^2 + bT^4 $$

The accuracy of this fit becomes obvious when $(p-p_0)/T^2$ is plotted as a function of $T^2$. Then, the data lies on a straight line and the zero temperature intercept gives the magnitude of the disorder term. This plot is shown in Fig. 2 (right). The 0 K intercept is at 0.001 bar/K$^2$.

Following this cool down, the sample was annealed for 6 hours at 1.65 K. Contrary to torsional oscillator experiments [6], the pressure increases during the annealing process. We interpret the pressure rise as mass redistribution of the sample: when the sample warms up it expands thermally and the pressure increases. The increasing pressure causes the diaphragm to expand which in turn gives rise to flow of helium atoms to the center of the cell and the cell volume increases. Pressure and volume change by 6 bar and 1%, respectively. We can describe the annealing data well by an exponential decay with a time constant of two hours.

In the cool down afterwards, the quadratic contribution to the pressure dependence is reduced by 30% to 0.0007 bar/K$^2$. This data differs from [7] where the disorder term disappeared after
Figure 2. The sample pressure is shown as a function of temperature in a sample grown with blocked-capillary method. On the left, different fits of the data are shown. The best fit to the data includes a term proportional to $T^2$. The functional form of the best fit (red line) is $p = p_0 + 0.00096 T^2 + 0.01042 T^4$. Right: the same data is presented as pressure divided by temperature squared versus temperature squared. This plot emphasizes the quadratic pressure term which can be read off as the non-zero offset at zero temperature. The data has been fitted linearly and the slope is the coefficient of the phonon contribution to the pressure.

annealing at 2 K for 10 hours. However, it is consistent with our torsional oscillator experiments, when supersolid signals were at most halved after a similar anneal [6]. Possibly the confined geometry prevents complete annealing as it geometrically locks the defects in place.

Our main result is that the pressure changes when we fix the temperature even at low temperatures. Fig. 3 shows pressure as a function of time at 19 mK. In 40 hours, the pressure decreases by $\approx 100 \mu$bar with an approximate exponential time dependence. The initial velocity of the diaphragm is $4.38 \times 10^{-10}$ µm/s. Fitting the pressure with an exponential we find a time constant of 35 hours. At higher temperatures, the pressure relaxes in a similar way but with a shorter time constant. As in the annealing process, we attribute the low temperature relaxations to mass flow in the cell. When the cell is cooling, the crystal contracts and causes the diaphragm to move inward which in turn makes helium atoms move from the center of the cell to the edges. This process has a long time constant compared to the time it takes to cool down. Hence, it continues while the sample is held at low temperatures. The relaxation processes at low temperatures lead to a reduction of the the disorder contribution to the pressure by 10%.

On the right, Fig. 3 displays decay time constants as a function of inverse temperature. While these results are preliminary, the data is compatible with thermal relaxation: The rate of the process, $k$, is given by Arrhenius’ law:

$$k = Ae^{-T_B/T}$$  

where $T$ is the temperature, and $T_B$ is the energy barrier of the process in Kelvin. To obtain a crude estimate of the height of the energy barrier of the process, we assume that the rate is equal to the inverse time constant. From Fig. 3, the energy barrier can then be identified as the slope when the logarithm of the inverse time constant is plotted as a function of inverse temperature. In our fit, the energy barrier is $28$ mK.
Figure 3. Overview of low temperature relaxations. Left: the pressure is shown as a function of time while the sample is held at 19 mK. If the data is fitted with an exponential decay the time constant, \( \tau \), is 35 hours. Right: Time constants are shown as a function of inverse temperature. The temperatures corresponding to the data points are 19 mK, 100 mK, and 300 mK, respectively. The slope of the graph can be identified as the energy barrier of the process. The barrier height is 28 mK.

We are the first group to observe pressure relaxations at low temperatures: Neither Grigor’ev et al. [7, 10] nor Day and Beamish [11] report on low temperature relaxations in their pressure measurements. However, both were limited by their resolutions of 30 \( \mu \)bar [7] and 200 \( \mu \)bar [11] and therefore would not have been able to resolve the low temperature relaxations. However, there is indirect evidence that the same phenomenon has been observed in torsional oscillators. In one torsional oscillator group, the same helium sample is studied for months without being warmed up above 1 K [12]. Over time, the supersolid signals were found to decrease. Possibly the same kind of relaxation processes take place in their oscillators.

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