Absence of slow sound modes in supersolid $^4$He

S. Kwon$^{a,b}$, N. Mulders$^a$ and E. Kim$^b$

$^a$KAIST, Dept. of Physics, Taejon 305701, South Korea
$^b$Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

Abstract Torsional oscillator experiments on solid $^4$He have been interpreted as showing mass decoupling similar to what one observes in a superfluid. Within the context of a two-component model for the supersolid one would expect the appearance of a second, slow acoustic mode. We have searched for this mode using an acoustic resonance technique. We have used porous membranes in bulk solid $^4$He analogous to a second sound experiment in the superfluid. We also investigated solid helium in Vycor using piezoelectrically driven titanium diaphragms (analogous to a fourth sound experiment in the liquid). Our measurements have shown no indication of an additional sound mode in kHz range.

Keywords solid helium, supersolid,

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1. INTRODUCTION

A classical supersolid is a state which shows periodic lattice structure (diagonal long-range order) as well as superflow (off-diagonal long-range order). The first evidence for a supersolid state was reported by Kim and Chan$^1$. They observed a period drop in torsional oscillator experiments with solid $^4$He and interpreted this as mass decoupling due to superflow. This interpretation is strongly supported by blocked channel experiments$^{1,2}$. Mass decoupling is also observed with solid $^4$He in various porous media such as Vycor$^3$, porous gold$^4$, aerogel$^5$, and even Gelsil$^6$, which has a pore size of only ~2 nm.

The interpretation of the experiments as the decoupling of some of the mass of the solid from the motion of the lattice is analogous to the two-fluid model for superfluid helium. The additional degree of freedom in the two-fluid model supports an additional sound mode, with a velocity that goes to zero at the superfluid transition. This additional sound mode is called `second sound'. Unlike first sound, second sound propagates through counter flow between the normal and superfluid components of the liquid. In porous media, the normal component is effectively locked, so only the superfluid can mediate sound which is then called “fourth sound”. Similarly, thinking of the supersolid as a multi-component system, one would assume that there exists at least one additional sound mode. In the following we will refer to it as the slow mode. A major complication in the search for this mode is that without a good theoretical understanding of the supersolid state it is difficult to predict how one may couple to the slow mode, or what propagation velocity one should expect. Experiments by H. Kojima's group, using a heat pulse technique failed to detect clear evidence of the slow mode$^7$. We have chosen a different approach. In our
experiments, sound is generated and detected using oscillating (porous) membranes.

2. EXPERIMENTAL ASPECTS

In the superfluid, it is relatively straightforward to study second and fourth sound using acoustic resonators. In the context of solid helium, this technique has the advantage that experiments are done in the kHz range, and thus overlap in frequency with torsional oscillator experiments.

Figure 1 (color online) The acoustic cells. Cell A: (a) electrode, (b) cell fill line, (c) Anopore membrane; Cell B: (d) piezoelectric transducer, (e) Ti diaphragm, (f) Vycor.

Figure 1 shows the two cells used in the experiments reported here. Cell A consists of a cylindrical cavity with a diameter of 9.6 mm and 19 mm in length. This cavity is capped by two sound transducers that consist of electrostatically driven porous membranes. In the superfluid state, these transducers work well for the generation and detection of second sound. Traditionally, Nuclepore has been used, but we found Anopore membranes with a much larger porosity, more efficient as well as more convenient to use. Either Pt or Al electrodes were sputtered on the membranes. Al is especially convenient since it becomes superconducting at low temperature, which greatly reduces the dissipation in the transducers. We used an unbiased ac drive and detected the 2nd harmonic of the drive signal, thus avoiding cross-talk. Cell B had 6.9 mm diameter, 18 mm length cavity and contained a matching Vycor cylinder. The space between cavity wall and the Vycor was completely filled with epoxy. The cell cavity was capped by 0.5 mm thickness titanium membranes to which PZT disks were epoxied. Titanium membrane/PZT sandwiches act as conventional acoustic transducers.

To determine the resonance frequencies of the cells we used two different methods. We have the option to use white noise bursts (with a bandwidth of 25 kHz) on the generating side and Fourier transform the signal from the detecting side. This method has the great advantage that one does not have to “hunt” for the resonances, which in high-Q systems can be tedious. Data collection can be
fast, but there is no phase sensitivity and the signal-to-noise ratio can only be improved by averaging. It proved especially useful in second sound experiments very close to $T_\lambda$ where the temperature stability of our dilution fridge is poor, ~1 mK. For example, the data of the inset in Fig. 2 was acquired within one minute. The second option is to do a conventional "frequency sweep" using a lock-in amplifier. Although rather slow, this method has the advantage that it is easy to distinguish mechanical resonances from EM interference. With the exception the inset of figure 2, all data shown here was taken by sweeping the frequency. Figure 2 shows a typical second sound spectrum. Clearly, in the liquid phase the second sound can be detected for superfluid fractions as low as 1% (near $T_\lambda$ primarily limited by the temperature stability).

Figure 3 shows the signal for cell A filled with solid at 48 bar, for temperatures of 300 mK and 50 mK. The expected slow mode velocity in the supersolid would be ~50 m/s which corresponds to a fundamental frequency of ~1.3 kHz, assuming 1% of supersolid fraction. Comparing the 300 mK data, presumably well above any supersolid transition, with data at 50 mK, we find no additional resonances. We have repeated these experiments at pressures from 27 to 48 bar, but no signature of a slow mode was found. All samples were rapidly cooled to make relatively large supersolid fraction. Note that the frequency spectrum in Fig. 3 is completely reproducible for any one solid sample but is different from sample to sample. Comparing with the superfluid data, fig. 2, the signal is three orders of magnitude smaller. The displacement of the generating membrane is 1.6 pm at 30 V$_{rms}$ drive. This is very small compared to a typical displacement of 1 nm in torsional oscillator experiments. It is also much smaller than the critical strain, $2 \times 10^{-6}$, observed by Day and Beamish.
One might argue that the displacement of the membrane is too small to generate a detectable signal. And indeed, it was not easy to observe the first sound in solid or in the normal liquid in cell A. The displacement of the membrane in the solid is similar to that in normal liquid. However, at least in the superfluid case a porous membrane transducer becomes extremely sensitive. If there is small superfluid fraction, for example, at $\rho_s/\rho \approx 0.01$, the displacement of membrane becomes 20 times larger than that in normal fluid.

**Figure 3** (color online) A frequency scan on a solid sample at 48 bar (in cell A) at 50 mK (black), 300 mK (red) with 30 $V_{\text{rms}}$ drive. The 300 mK data is shifted for clarity. This solid sample was cooled from the liquid phase to solid at 1 K within 7 min. Comparing with fig. 2, the amplitude is several orders of magnitude smaller. Here 20 $\mu$V corresponds to a displacement of ~0.4 pm.

**Figure 4** The fourth sound spectrum at 0.4 bar and 0.9 K with 5 $V_{\text{rms}}$ drive. Fourth sound velocity is $v_4 = 99$ m/s. The inset shows data taken near the superfluid transition in Vycor, $v_4 = 14$ m/s corresponding to $\rho_s/\rho = 0.02$. 
A typical low temperature fourth sound spectrum of superfluid in Vycor is shown in Fig. 4. For higher temperature we can calculate superfluid fraction with \( \rho_s/\rho = \left[ \frac{v_4(T)}{v_4(0)} \right]^2 \). The inset of Fig. 4 shows part of the spectrum when \( \rho_s/\rho \approx 0.02 \).

Figure 5 shows the spectrum of solid He in Vycor at low temperature. Again, we did not observe a slow acoustic mode in the solid. At our typical drive level, 5 \( V_{\text{rms}} \), the displacement of the drive membrane was approximately 0.8 nm.

**Figure 5** (color online) Frequency scans on a 90 bar solid sample in Vycor, at 50 mK (black), 300 mK (red) with 5 \( V_{\text{rms}} \) drive. This solid sample was quench cooled from the liquid to solid at 1K within 90 sec. The 300 mK data is shifted for clarity.

### 3. DISCUSSION

The interpretation of a null result tends to be a little speculative. A simple explanation might be that the slow mode in supersolid helium is heavily damped. However, one would expect that this would also lead to significant damping in torsional oscillator experiments. It is possible that our experiments do not have the required sensitivity. In the case of the porous membrane
transducers + bulk solid this is certainly conceivable. The transducers rely on the
ability of the membrane to move with respect to a fixed electrode. It is possible
that, supersolid or not, the helium crystal locks the membrane in place and very
little motion is possible. On the other hand, it is more difficult to see why in the
experiments on solid helium in Vycor it would be impossible to set up (resonant)
motion in the supersolid component. One might interpret these experiments as
an extension of the (no) DC flow experiments by Day and Beamish\textsuperscript{13} and the
(no) very slow flow ones by Rittner and Reppy\textsuperscript{14}. It seems that one cannot
induce superflow by pushing, even at frequencies where the torsional oscillator
experiments see decoupling. Finally, it may be that our thinking, strongly
influenced as it is by the two fluid model for the superfluid, is entirely
inappropriate. There simply is no slow mode.

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