

# Acoustical Experiments on Superfluid $^3\text{He}$ - $^4\text{He}$ Mixtures in Aerogel

G. Lawes<sup>a</sup>, E. Nazaretski<sup>a</sup>, P.N. Brusov<sup>a</sup>,  
N. Mulders<sup>b</sup>, and J.M. Parpia<sup>a</sup>

<sup>a</sup>Dept. of Physics and LASSP, Cornell University, Ithaca, NY 14853

<sup>b</sup>Dept. of Physics, University of Delaware, Newark, DE 19716

*This report discusses our results on the superfluidity of  $^3\text{He}$ - $^4\text{He}$  mixtures in a 98% porosity silica aerogel. We have used low frequency sound to probe helium mixtures confined to aerogel, and have observed both the slow mode of superfluid  $^3\text{He}$  in aerogel, which is manifested only below  $T_c$ , and an additional sound mode present only in the mixture. We attribute this novel sound mode to the slow-mode in the  $^4\text{He}$  rich phase of the dilute  $^3\text{He}$ - $^4\text{He}$  mixture. This mode exhibits positive frequency shifts below  $T_c$  in aerogel, while above  $T_c$  the mode is observed at a temperature independent frequency until close to  $T_\lambda$  where it shifts to zero frequency.*

*PACS numbers: 67.57.De, 67.40.Pm, 67.60.Fp*

$^3\text{He}$  confined to silica aerogels presents a novel system for the investigation of impurity scattering on p-wave superfluidity. The aerogel acts like a collection of impurity scattering sites, and  $^3\text{He}$  undergoes a superfluid transition (albeit with reduced  $T_c$  and  $\rho_s$ ) in the presence of this disorder<sup>1</sup>. Furthermore, the aerogel matrix has been shown to alter the phase diagram for  $^3\text{He}$ - $^4\text{He}$  mixtures, detaching the phase separation curve from the  $^4\text{He}$  lambda line so that at  $T=0$  all of the  $^3\text{He}$  is close to (within a few  $^3\text{He}$  coherence lengths) the  $^4\text{He}$  rich phase<sup>2</sup>. The first experiments to investigate the superfluidity of  $^3\text{He}$  in  $^4\text{He}$ -coated aerogel strands used torsional oscillator techniques to investigate the superfluid transition. These measurements showed that the  $^3\text{He}$  exhibited a phase transition at  $^4\text{He}$  concentrations ranging up to 34%<sup>3</sup>.

The present experiment uses low frequency CW sound propagation to

probe the behavior of  $^3\text{He}$ - $^4\text{He}$  mixtures in aerogel. In particular, we have concentrated on investigating the second-sound like modes present in the aerogel-helium system to understand the nature of the superfluidity. It has been predicted that there should be three sound modes present in (bulk) homogeneous mixtures, the first corresponding to ordinary first sound and two second sound modes, one terminating at  $T_\lambda$  and the other terminating at  $T_c$ <sup>4-6</sup>. The mode terminating at  $T_c$  is associated with superfluid  $^3\text{He}$  dissolved in the superfluid  $^4\text{He}$ . In these measurements however, we believe that the strong inhomogeneities in the system permit the existence of a second sound like slow mode terminating at  $T_c$  which propagates only in the  $^3\text{He}$  rich phase of the mixture.

The experimental cell consists of a cylindrical body, filled with a 98% porosity aerogel sample. The cylinder is capped off by a pair of thin BeCu diaphragms to which have been attached piezoceramic material to act as the microphone and speaker transducers. There is also a cylindrical capacitor, filled with the same 98% aerogel, connected to the experimental volume and which is used to monitor the  $^3\text{He}$ - $^4\text{He}$  concentration inside the cell. The experiment is mounted on the stage of a nuclear demagnetization refrigerator with a base temperature of under 0.5 mK. The temperature was measured using a  $^3\text{He}$  melting curve thermometer mounted on the nuclear stage.

The measurements discussed in this paper focus on the low  $^4\text{He}$  concentration portion of the phase diagram. The  $^4\text{He}$  fraction in the cell is determined by comparing the empty cell capacitance with the measured capacitance together with the values for the capacitance at various pressures with pure  $^3\text{He}$  and pure  $^4\text{He}$ . This information gives the number density of particles in the cell, from which we can extract the  $^4\text{He}$  fraction by using the molar volumes of  $^3\text{He}$  and  $^4\text{He}$  at the working pressure. The determination of the  $^4\text{He}$  fraction in the cell *in situ* is absolutely crucial. The presence of a silver sinter heat exchanger provides a large surface area (comparable to the experimental cell) into which the  $^4\text{He}$  may be redistributed.

The distribution of  $^4\text{He}$  in an 11%  $^3\text{He}$ - $^4\text{He}$  mixture in aerogel is somewhat unclear. Previous experiments using torsional oscillators<sup>2</sup> and heat capacity measurements<sup>7</sup> to probe the  $^3\text{He}$ - $^4\text{He}$  phase diagram in aerogel suggest that for  $^4\text{He}$  concentrations less than about 20% there is no well-defined phase separation. It is expected that there will be a high concentration of  $^4\text{He}$  particles near the aerogel strands with pure  $^3\text{He}$  in the voids.

There are two second sound like modes present in  $^3\text{He}$ - $^4\text{He}$  mixtures in aerogel. The first is due to oscillations in the superfluid  $^3\text{He}$  component and vanishes at  $T_c$ . The second results from thermal oscillations (which couple to the pressure transducers on account of the aerogel matrix<sup>8</sup>) in the  $^4\text{He}$ -rich superfluid phase of the mixture and vanishes at  $T_\lambda$ . A plot showing the

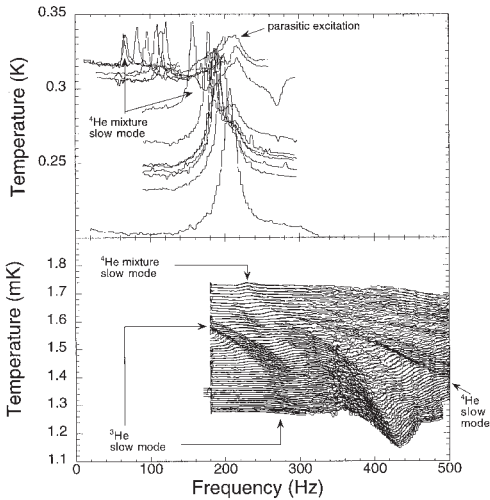


Fig. 1. Spectra of the quadrature response of the mixture slow mode, offset vertically with temperature. Sample is an 11%  $^4\text{He}$  mixture at 17.2 bar. Note the different temperature scales for the two plots. The lower plot shows the appearance of a  $^3\text{He}$  slow mode at  $T_c$ ; this mode is accompanied by a shift in frequency in the mixture slow mode, as labelled.

temperature evolution of these slow modes in an 11%  $^4\text{He}$  mixture at 17.2 bar is shown in Fig. 1. There is also a mode visible at 200 Hz, starting at a temperature of around 275 mK. This mode remains a high quality mode until at least 400 mK, and is likely associated with a parasitic excitation in the cell, rather than the second sound like excitation of the mixture slow mode.

We also plot the center frequency of the  $^3\text{He}$  modes as a function of temperature in Fig. 2. The center frequency of each peak was determined manually for each trace. The empty circles are data for the slow mode of  $^3\text{He}$  in a 3%  $^4\text{He}$  mixture. At this very low concentration, the  $^4\text{He}$  is thought to be present only as a solid layer covering the aerogel strands. The spectrum is very similar to that which we found for pure  $^3\text{He}$ , although with a slightly elevated value of  $T_c$  (by about  $50 \mu\text{K}$ ). In particular, there is no evidence for an additional slow mode of the  $^4\text{He}$  at this concentration.

The center frequency of the  $^3\text{He}$  slow mode in an 11%  $^4\text{He}$  mixture is also shown in Fig. 2. The presence of 11%  $^4\text{He}$  in the mixture has only a small effect on the superfluidity of  $^3\text{He}$ . The transition temperature  $T_c$  is unchanged from the value at 3%  $^4\text{He}$ , although the superfluid density  $\rho_s$  is slightly reduced. Note that unlike pure  $^3\text{He}$  in aerogel,  $\rho_s$  will not be simply

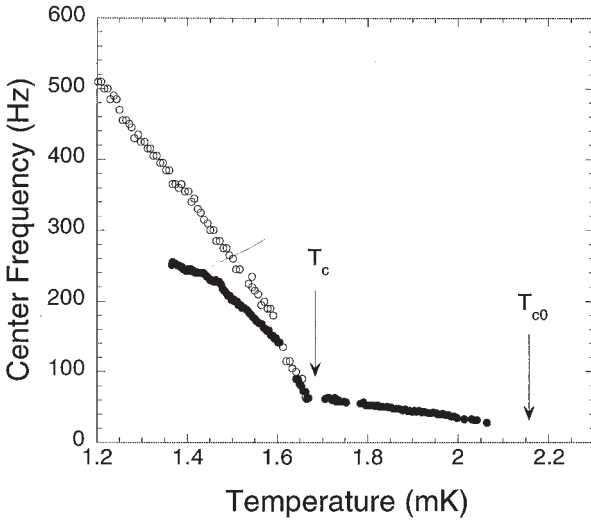


Fig. 2. Center frequencies for the  $^3\text{He}$  slow mode versus temperature at 17.2 bar. Open circles— $^3\text{He}$  slow mode in 3% mixture. Closed circles— $^3\text{He}$  slow mode in 11% mixture.

proportional to  $c_2^2$  (the speed of second sound in aerogel squared) because of “tortuosity” effects from the  $^4\text{He}$  coated aerogel strands, although these are likely to be small. The  $^3\text{He}$  slow mode in the 11% mixture shows the existence of an “edge” mode, thought to be caused by oscillations in bulk  $^3\text{He}$  in the narrow gap between the aerogel and cell walls, as observed in previous acoustical measurement on  $^3\text{He}$  in aerogel<sup>9</sup>. The slow mode merges into the edge mode at temperatures above  $T_c$  and vanishes at the bulk superfluid  $^3\text{He}$  transition temperature ( $T_{c0}$ ). The edge mode was also present in the 3%  $^4\text{He}$  mixture, but its amplitude was too small to be able to resolve accurately.

Fig. 2 does not show the temperature evolution of the slow mode in the 11% mixture because we are unable (as yet) to unambiguously extract the center frequency from interfering resonances. This mode shows positive frequency shifts on cooling below  $T_c$ , similar to that of the  $^3\text{He}$  slow mode. At temperatures above  $T_c$ , the frequency of the slow mode in the mixture remains fixed. In particular there is no shift in frequency (or amplitude) at  $T_{c0}$ . This is important to note, because it demonstrates that this mode is a feature of the mixture confined to the aerogel rather than any sort of bulk effect. The nature of the mixture slow mode below  $T_c$  is somewhat unclear, we cannot determine if the motion is restricted to the  $^4\text{He}$  component, or if the superfluid  $^3\text{He}$  also participates in the motion.

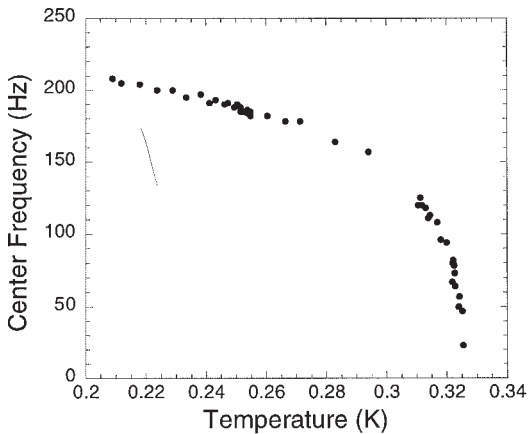


Fig. 3. Center frequencies of the mixture slow mode in an 11%  $^4\text{He}$  mixture at 17.2 bar versus temperature.

The mixture slow mode is present at higher temperatures when there is no superfluid  $^3\text{He}$  present. There is no ambiguity about the origin of the slow mode at these elevated temperatures. The slow mode of pure  $^4\text{He}$  in aerogel has been observed previously<sup>10,11</sup>. In the  $^3\text{He}$ - $^4\text{He}$  mixture in aerogel system the  $^3\text{He}$  in the normal phase reduces the speed of the  $^4\text{He}$  slow mode, which remains a high quality mode at low frequencies at all temperatures. The center frequencies of the  $^4\text{He}$  (or mixture) slow mode as a function of temperature are plotted in Fig. 3. This mode decreases to zero frequency at a temperature of 325 mK, which is consistent with previous measurements on the  $^3\text{He}$ - $^4\text{He}$  phase diagram in aerogel.

One further point to note about the  $^4\text{He}$  slow mode is that we can use the value of the frequency shift compared to the  $^4\text{He}$  superfluid density to investigate (at least qualitatively) the distribution of  $^4\text{He}$  inside the aerogel. We can use the following relation between the superfluid density in aerogel and the speed of second sound:

$$\frac{\rho_s}{\rho} = \frac{\rho}{\rho_a} \left( \frac{c_s}{c_a} \right)^2, \quad (1)$$

(taken from previous work on  $^3\text{He}$  in aerogel<sup>9</sup>) where  $c_s$  and  $c_a$  are the speed of second sound in  $^4\text{He}$  and the speed of sound in aerogel respectively to probe the distribution of  $^4\text{He}$  in aerogel. If we substitute the total ( $^3\text{He}$  plus  $^4\text{He}$ ) density into Eq. 1, with the estimated speed of sound in aerogel (50 m/s) and a resonant frequency for the  $^4\text{He}$  slow mode of 220 Hz at low temperatures (corresponding to  $c_s \approx 6$  m/s for direct sound propagation) the

superfluid fraction is estimated to be on the order of 4%. However, at these very low temperatures we expect all of the  $^4\text{He}$  to be in the superfluid state, so the superfluid fraction of the mixture should be closer to 8% (excluding the  $^4\text{He}$  solid on the aerogel strands). This discrepancy can be attributed to the fact that the sound mode must take a rather tortuous path through the sample cell—there is no direct path through the superfluid component between the transducers. By comparing the frequency of the  $^4\text{He}$  slow mode with the  $^4\text{He}$  concentration in the mixture, we will be able to detect changes in the  $^4\text{He}$  morphology, and in particular observe changes as the  $^3\text{He}$ - $^4\text{He}$  mixture is remixed and the distribution of  $^4\text{He}$  on the aerogel changes. We have found that the frequency of this mixture slow mode changes while the sample is annealed, which suggests that there may be a redistribution of  $^4\text{He}$  on the aerogel strands occurring in the homogeneous mixture at high temperatures.

In summary, we have investigated two second sound like modes in  $^3\text{He}$ - $^4\text{He}$  mixtures in aerogel for small  $^4\text{He}$  concentrations. The first mode corresponds to thermal oscillations in the  $^3\text{He}$  superfluid component and is present only below  $T_c$ . The second slow mode results from oscillations in the  $^4\text{He}$ -rich component of the mixture and vanishes only at  $T_\lambda$ , although the frequency of this mode shifts at temperatures below  $T_c$ . We hope to develop a better understanding of this mixture slow mode by continuing our investigations into mixtures with higher  $^4\text{He}$  contents.

We acknowledge helpful conversations with E.N. Smith, M.H.W. Chan, Paul Brusov, and J. Beamish. The research was supported by the NSF under DMR-9970817 and by NASA under NAG8-1438.

## REFERENCES

1. J.V. Porto, and J.M. Parpia, *Phys. Rev. Lett.* **74**, 4667 (1995).
2. S.B. Kim, J. Ma, and M.H.W. Chan, *Phys. Rev. Lett.* **71**, 2268 (1993).
3. A. Golov, J.V. Porto, and J.M. Parpia, *Phys. Rev. Lett.* **80**, 4486 (1997).
4. I.M. Khalatnikov, *JETP Letters* **17**, 386 (1973).
5. G.E. Volovik, V.P. Mineev, and I.M. Khalatnikov, *Sov. Phys. J.E.T.P.* **42**, 342 (1975).
6. A.F. Andreev and E. P. Bashkin, *Sov. Phys. J.E.T.P.* **42**, 164 (1975).
7. N. Mulders, and M.H.W. Chan, *Phys. Rev. Lett.* **75**, 3705 (1995).
8. P. Brusov, *et al.*, *Phys. Rev. B* **63**, 14507 (2001).
9. A. Golov, D.A. Geller, and J.M. Parpia, *Phys. Rev. Lett.* **82**, 3492 (1999).
10. M.J. McKenna, Tania Slaweki, and J.D. Maynard, *Phys. Rev. Lett.* **66**, 1878 (1991).
11. N. Mulders, *et al.*, *Phys. Rev. Lett.* **67**, 695 (1991).