

## Sound Propagation in Coexistent Bose and Fermi Superfluids in Aerogel

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We report the first observation of longitudinal sound propagation in three dimensionally distributed Bose and Fermi superfluids in an acoustic investigation of phase separated  $^3\text{He}$ - $^4\text{He}$  mixtures confined to aerogel. At mK temperatures, this inhomogeneous system exhibits simultaneous  $^3\text{He}$  and  $^4\text{He}$  superfluidity leading to two “slow modes” along with the conventional sound mode. We also infer the superfluidity of isolated bubbles of pure  $^3\text{He}$  in a large  $^4\text{He}$  concentration sample.

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Liquid  $^4\text{He}$  (bosons) and  $^3\text{He}$  (fermions) exhibit distinct mechanisms for condensation into their superfluid states. Our understanding of macroscopically occupied ground states in bosonic systems, exemplified in the strongly coupled limit by superfluid  $^4\text{He}$ , has been extended to the weak coupling limit by recent investigations of Bose-Einstein condensates (BEC) in dilute gases [1]. Current research into ultracold atomic Fermi gases is aimed at promoting Cooper pairing in these systems [2] by cooling boson-fermion mixtures. Researchers have produced a BEC of bosonic  $^7\text{Li}$  or  $^{23}\text{Na}$  atoms coexisting with a degenerate Fermi gas of fermionic  $^6\text{Li}$  atoms, but have not yet succeeded in creating such a system with two superfluid components [3,4].

Concomitant with the investigation of pure Bose and Fermi superfluids, experiments on homogeneous mixtures of  $^4\text{He}$  and  $^3\text{He}$  have attempted to produce a system in which both components are superfluid [5]. At milli-Kelvin temperatures,  $^3\text{He}$ - $^4\text{He}$  mixtures with  $^3\text{He}$  content in excess of 6% phase separate into a pure  $^3\text{He}$  phase and a  $^4\text{He}$  rich phase [6]. Estimates for the superfluid transition temperature,  $T_c$ , for  $^3\text{He}$  dissolved in the  $^4\text{He}$  rich phase range from 1 to 10  $\mu\text{K}$  [7], an order of magnitude below present capabilities. However, with the use of porous materials such as aerogel, it has become possible to bring the two separated phases into close contact [8]. In this Letter, we discuss a series of experiments on phase separated  $^3\text{He}$ - $^4\text{He}$  mixtures in a 98% porous silica aerogel.

The aerogels consist of a network of silica strands with a diameter of a few nm whose density correlations exhibit fractal structure from a few nm to roughly 100 nm [9]. When  $^3\text{He}$ - $^4\text{He}$  mixtures are introduced into an aerogel, the  $^4\text{He}$ -rich component preferentially coats the surface of the strands, while the  $^3\text{He}$  component fills the remaining voids [10,11]. Pure  $^4\text{He}$  undergoes a sharp superfluid phase transition when confined to aerogel [12]. Pure  $^3\text{He}$  and  $^3\text{He}$  in contact with  $^4\text{He}$ , in 98% open aerogel, also undergo well-defined transitions. Because the  $^3\text{He}$  superfluid is comprised of  $p$ -wave Cooper pairs, nonmagnetic scattering from the aerogel impurity is pairbreaking, and

suppresses both the superfluid transition temperature and superfluid density [13–15].

Landau’s two-fluid model [16] which describes the hydrodynamics of superfluids, predicts the existence of two normal modes in which the superfluid and normal component move either in phase (first sound) or out of phase (second sound). In pure  $^3\text{He}$  or  $^4\text{He}$ , first sound (similar to ordinary sound) exists both above and below the superfluid transition temperature, while second sound only propagates in the superfluid phase. When the superfluid is confined to a compliant solid such as aerogel with a longitudinal sound velocity comparable to that of the liquid, both the slow and fast longitudinal modes exhibit significant temperature and pressure variations [17,18]. Consequently, they can be excited and detected by pressure transducers [19], or by a heater and thermometer [20]. The slow mode is clear evidence for superfluidity: It exists only at temperatures below  $T_c$ .

Three longitudinal sound modes should exist if two independent superfluid components are present [21]. When the normal component is viscously locked in a very rigid porous material [22], such two-component superfluids should reveal two slow modes of coupled oscillations of density and concentration, in addition to the fast mode. We thus expect a mixture of superfluid  $^3\text{He}$  and  $^4\text{He}$  confined in a *compliant* aerogel to possess *three* longitudinal modes. In this Letter, we concentrate on measurements of the slow modes in the aerogel filled with  $^4\text{He}$ - $^3\text{He}$  mixtures, and present a hydrodynamic multicomponent superfluid model that provides the framework for the understanding of these modes.

Our cell consists of a cylindrical cavity of length 1.52 cm filled with a 98% porosity aerogel. Diaphragms at each end with piezoceramic material attached serve as the speaker and microphone. As we sweep the drive frequency, sound resonances appear as peaks in the signal at the microphone. The superfluid transition temperatures are determined by tracking the low frequency slow mode while the temperature slowly increases. The  $^4\text{He}$  concentration in the aerogel is measured using a coaxial

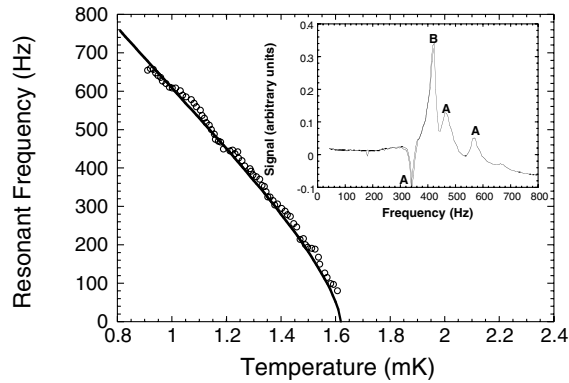


FIG. 1. The pure  $^3\text{He}$  in aerogel slow mode resonant frequency as a function of temperature. The mode's frequency  $\Rightarrow$  0 when the superfluid density vanishes at  $T_c \approx 1.62$  mK. The solid line is the prediction from the model described below. Inset: A representative spectrum for  $^3\text{He}$  in aerogel at 1.35 mK. Resonances labeled A are the first three slow mode harmonics. B is a temperature insensitive Helmholtz resonance.

capacitor also filled with a 98% aerogel and attached to the resonator volume. The experiment was cooled by a nuclear demagnetization stage and the sample temperature was measured using a  $^3\text{He}$  melting curve thermometer.

The behavior of the superfluid sound modes in the cell was characterized by filling the aerogel with pure  $^3\text{He}$  at 17.2 bars. At low temperatures, we observed a resonance in the acoustic spectrum which shifted monotonically towards zero frequency as the cell warmed and vanished at 1.62 mK (see Fig. 1). This is consistent with other measurements of  $^3\text{He}$  in a 98% porosity aerogel at this pressure [9]. We interpret this resonance as arising from the slow mode of superfluid  $^3\text{He}$  in aerogel.

At a  $^4\text{He}$  fraction of 3% of the total number density, the aerogel strands were completely covered with a solid layer of  $^4\text{He}$  atoms with the remainder of the sample filled with  $^3\text{He}$ . The spectrum for this mixture was practically unchanged from that of pure  $^3\text{He}$ . In particular, there was no signature of a superfluid  $^4\text{He}$  component at any temperature. The only effect of plating the aerogel with solid  $^4\text{He}$  was to increase the  $^3\text{He}$  superfluid transition temperature by  $70 \mu\text{K}$  due to a change in the  $^3\text{He}$  quasiparticle scattering conditions, consistent with previous observations of  $T_c$  of  $^4\text{He}$ - $^3\text{He}$  mixtures in aerogel [15].

Increasing the  $^4\text{He}$  concentration of the mixture to 10.5% had a dramatic effect on the low temperature acoustic spectrum. At this  $^4\text{He}$  content, the strands are coated with (on average) three layers of fluid  $^4\text{He}$ , and we observed a resonance in the spectrum well above the  $^3\text{He}$  superfluid  $T_c$ . We unambiguously identified this new mode as arising from superfluidity in the  $^4\text{He}$  component of the mixture by tracking it in temperature until it vanished at 337 mK, close to the expected  $^4\text{He}$  superfluid transition temperature in this mixture (see right panel of Fig. 2) [8,10]. By mK temperatures, this mode's frequency

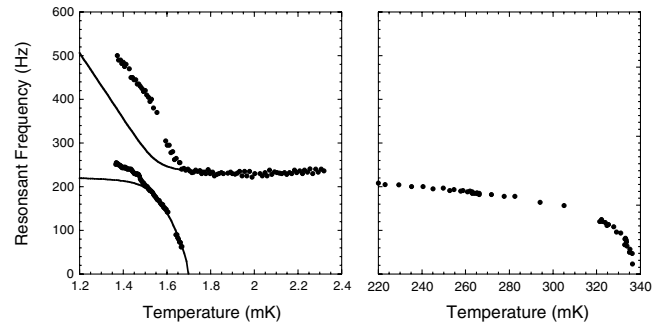


FIG. 2. The right-hand panel shows the resonant frequency for the high velocity slow mode in a mixture containing 10.5%  $^4\text{He}$ . This mode vanishes at the  $^4\text{He}$  superfluid  $T_c$  (337 mK). The left panel shows the continuation of this mode to lower temperatures together with the onset of the low velocity slow mode with the model frequencies indicated by the solid lines.

is nearly constant, consistent with the saturation of the  $^4\text{He}$  superfluid fraction. At very low temperatures ( $\sim 1.6$  mK), the acoustic spectrum for a 10.5%  $^4\text{He}$  mixture in aerogel shows a resonance that increases from zero frequency as the temperature is lowered below the onset of the  $^3\text{He}$  superfluidity. Simultaneously, the higher velocity slow mode exhibits a continuous increase in its resonant frequency.

As the  $^4\text{He}$  fraction in the aerogel was increased to 23%, 57%, and 71%, we observed qualitatively similar behavior to that seen in the 10.5%  $^4\text{He}$  sample (see Fig. 3). In all cases, there is a continuous and sizable positive shift in the resonant frequency of the faster slow mode as the mixture is cooled below the  $^3\text{He}$   $T_c$ . We observe clear slow modes with an onset within  $25 \mu\text{K}$  of the value for only a thin  $^4\text{He}$  superfluid layer coating the aerogel. This suggests that the global value of  $T_c$  is determined mainly by

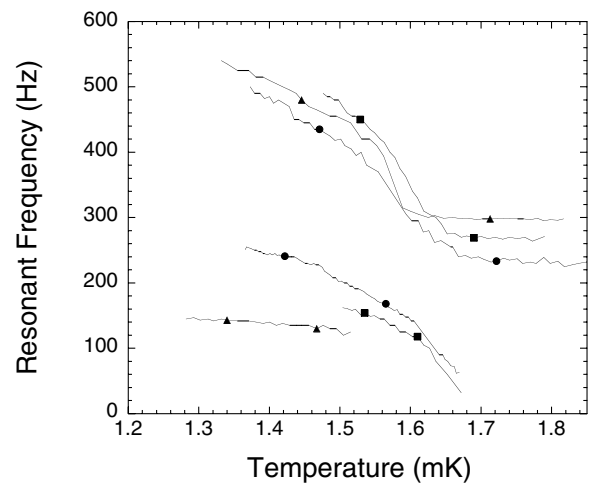


FIG. 3. These curves show the resonant frequency of both the slow modes in mixtures with 10.5% (circles), 23% (squares), and 71% (triangles)  $^4\text{He}$  versus temperature.

the onset of superfluidity in the  $^3\text{He}$  located in the percolated network of largest voids.

While a complete hydrodynamics of inhomogeneous phase separated mixtures is beyond the scope of this Letter, we present a simplified model, valid only for low frequencies and small concentrations of  $^4\text{He}$ , that captures the observed behavior. Consider a system consisting of phase separated incompressible  $^3\text{He}$  and  $^4\text{He}$  in an aerogel (with *constant* mass and number densities  $\rho_3$ ,  $n_3$  and  $\rho_4$ ,  $n_4$ ). The fluids occupy volume fractions  $\phi_3(\mathbf{r}, t)$  and  $\phi_4(\mathbf{r}, t)$  and have densities (per unit volume of the sample)  $\tilde{\rho}_3(\mathbf{r}, t) = \phi_3\rho_3$  and  $\tilde{\rho}_4(\mathbf{r}, t) = \phi_4\rho_4$ . The aerogel has a density  $\rho_a(\mathbf{r}, t)$  and takes up the remaining volume with a fraction  $\phi_a(\mathbf{r}, t) = 1 - \phi_3 - \phi_4$ . Two superfluid components, with superfluid densities  $\tilde{\rho}_{3s}(\mathbf{r}, t)$  and  $\tilde{\rho}_{4s}(\mathbf{r}, t)$  move independently with velocities  $\tilde{\mathbf{v}}_{3s}(\mathbf{r}, t)$  and  $\tilde{\mathbf{v}}_{4s}(\mathbf{r}, t)$  [23]. The normal components are thus  $\tilde{\rho}_{3n} = \tilde{\rho}_3 - \tilde{\rho}_{3s}$  and  $\tilde{\rho}_{4n} = \tilde{\rho}_4 - \tilde{\rho}_{4s}$ . At these frequencies, normal  $^3\text{He}$  and  $^4\text{He}$  are viscously locked to the aerogel and move together at velocity  $\mathbf{v}_n(\mathbf{r}, t)$  with an associated density  $\tilde{\rho}_n = \tilde{\rho}_{3n} + \tilde{\rho}_{4n} + \rho_a$ . We assume that the  $^3\text{He}$ - $^4\text{He}$  interface follows the aerogel, in equilibrium, and that any drag between the  $^3\text{He}$  and  $^4\text{He}$  superfluids is negligible. The continuity equations for  $^3\text{He}$ ,  $^4\text{He}$ , and aerogel are

$$\dot{\tilde{\rho}}_3 + \nabla \cdot (\tilde{\rho}_{3s}\tilde{\mathbf{v}}_{3s} + \tilde{\rho}_{3n}\mathbf{v}_n) = 0, \quad (1)$$

$$\dot{\tilde{\rho}}_4 + \nabla \cdot (\tilde{\rho}_{4s}\tilde{\mathbf{v}}_{4s} + \tilde{\rho}_{4n}\mathbf{v}_n) = 0, \quad (2)$$

$$\dot{\rho}_a + \nabla \cdot (\rho_a\mathbf{v}_n) = 0. \quad (3)$$

Neglecting the entropies of both  $^3\text{He}$  and  $^4\text{He}$ , the linearized dynamics are

$$\dot{\tilde{\mathbf{v}}}_{3s} = -\nabla\mu_3, \quad \dot{\tilde{\mathbf{v}}}_{4s} = -\nabla\mu_4, \quad (4)$$

$$\tilde{\rho}_{3s}\dot{\tilde{\mathbf{v}}}_{3s} + \tilde{\rho}_{4s}\dot{\tilde{\mathbf{v}}}_{4s} + \tilde{\rho}_n\dot{\mathbf{v}}_n = -\nabla P - \nabla P_a. \quad (5)$$

The  $^3\text{He}$  chemical potential depends only on pressure,

$$\nabla\mu_3(\mathbf{r}, t) = \frac{1}{\rho_3}\nabla P(\mathbf{r}, t), \quad (6)$$

but the  $^4\text{He}$  is adsorbed on to the aerogel strand as a film of thickness  $h(\mathbf{r}, t)$ , estimated for thin films to be of the order of  $h = \phi_4/A$  [where  $A(\mathbf{r}, t) \approx 1000 \text{ m}^2 \text{ g}^{-1} \times \rho_a(\mathbf{r}, t)$  [24] is the aerogel surface area per unit volume], experiences a van der Waals potential  $w(h) = -\gamma h^{-3}$ , where  $\gamma = 1.5 \times 10^{-50} \text{ J m}^3$  [25]. As a result, we have

$$\nabla\mu_4(\mathbf{r}, t) = \frac{1}{\rho_4}[\nabla P(\mathbf{r}, t) + (n_4 - n_3)\nabla w(\mathbf{r}, t)], \quad (7)$$

$$\nabla w = \frac{(3\gamma A)^3}{\phi_4^3} \left( \frac{\nabla\phi_4}{\phi_4} - \frac{\nabla\phi_a}{\phi_a} \right). \quad (8)$$

The stress in the aerogel,  $\nabla P_a(\mathbf{r}, t)$ , is related to the strain

$\phi_a^{-1}\nabla\phi_a$  using the empty aerogel sound speed  $c_a$ :

$$\nabla P_a = c_a^2 \rho_a \frac{\nabla\phi_a}{\phi_a}. \quad (9)$$

The details can be found elsewhere [26]. The equations can now be linearized and, after inserting plane wave solutions, one solves for the sound speeds of the two slower modes. For pure  $^3\text{He}$ , there is only a single slow mode with a dependence (for small  $\tilde{\rho}_{3s}$ ) given by

$$c_2 = \frac{c_a \rho_a^{1/2}}{\rho_3} \tilde{\rho}_{3s}^{-1/2}. \quad (10)$$

The predictions of this model for pure  $^3\text{He}$  in aerogel are plotted in Fig. 1. In the mixture, there are two solutions: With decreasing temperature, one mode starts from zero at the  $^4\text{He}$   $T_c$  and is continuous through the  $^3\text{He}$   $T_c$ , while the other mode only propagates below the  $^3\text{He}$   $T_c$ . For values of  $\phi_4$  of a few percent, these speeds can be approximated as follows. The faster mode, continuous through the  $^3\text{He}$   $T_c$ , has limiting behavior given by

$$c_2 = \frac{[3(n_4 - n_3)\gamma A^3]^{1/2}}{\phi_4^2 \rho_4} \tilde{\rho}_{4s}^{-1/2}, \quad (11)$$

for  $T \geq T_c$ , and Eq. (10) for  $T \rightarrow 0$ . The other mode starts from zero as Eq. (10), but in the limit of  $T \rightarrow 0$  approaches the temperature-independent Eq. (11). In Fig. 2, we show the predicted resonant frequencies for pure  $^3\text{He}$  and a  $^3\text{He}$ - $^4\text{He}$  mixture with a volume fraction of liquid  $^4\text{He}$   $\phi_4 = 0.06$  (corresponding to a  $^4\text{He}$  concentration of 10.5% after subtracting the solid  $^4\text{He}$  layer). The agreement between the experiment and model (exhibited in Fig. 2) is quite good given the simplifying assumptions.

We have also ventured to extend the experimental parameter space well beyond the applicability of the simplified model. By examining the behavior of high  $^4\text{He}$  concentration mixtures, we also investigate the superfluidity of isolated bubbles of  $^3\text{He}$  in  $^3\text{He}$ - $^4\text{He}$  mixtures in aerogel. Since the bulk solubility of  $^3\text{He}$  in  $^4\text{He}$  at 17.2 bars is approximately 8% [27], the  $^3\text{He}$  rich phase fills only 4% of the free volume when a 89%  $^4\text{He}$  mixture is introduced into the aerogel and is confined to the largest voids which are on the order of 100 nm. The regions of high silica density are occupied by the  $^4\text{He}$  rich phase.

The left-hand panel of Fig. 4 shows the low temperature, low frequency acoustic spectrum for the 89%  $^4\text{He}$  mixture. There is no evidence for a well-defined low velocity slow mode, although there are some very small unidentified low frequency features in the spectrum below  $T_c$ . Since the  $^3\text{He}$  phase does not percolate, there will be no hydrodynamic mass flow of the  $^3\text{He}$  superfluid. However, the higher velocity slow mode is still sensitive to the  $^3\text{He}$  superfluidity [as expressed in Eqs. (10) and (11)], and we observe an increase in its frequency at  $T \approx 1.6 \text{ mK}$ . This observation suggests the exciting possibility that the  $^3\text{He}$  superfluid order parameter can develop in isolated coherence length sized droplets when confined by

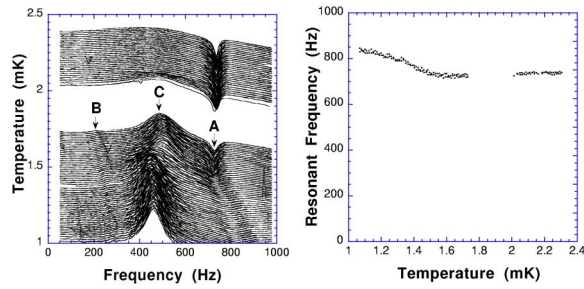


FIG. 4 (color online). The left panel shows the response of the microphone transducer, offset vertically by temperature. The resonance labeled A is the high velocity slow mode, the peak labeled B is a superfluid Helmholtz mode from the  $^3\text{He}$  outside of the cell, and the resonance labeled C is the Helmholtz mode in Fig. 1. The right panel shows the center frequency of the high velocity slow mode versus temperature.

superfluid  $^4\text{He}$ , perhaps even in aerogels whose density precludes superfluidity in pure  $^3\text{He}$  [28]. In principle, the bubble size could be varied by changing the  $^4\text{He}$ - $^3\text{He}$  ratio at fixed pressure in a given aerogel.

Confining  $^3\text{He}$  and  $^4\text{He}$  to a porous aerogel has led to the first observation of three-dimensional interpenetrating (although spatially inhomogeneous) superfluids. We have observed an additional low velocity longitudinal sound mode that is not present in pure superfluids confined to aerogel but arises only when two distinct superfluid components are present. The model we propose for understanding the hydrodynamics agrees very closely with the experimental data, although it is applicable only for small  $^4\text{He}$  concentrations.

It will be interesting to see if a similar model is appropriate for describing the hydrodynamics of multiple component superfluidity in Bose-Einstein condensates, or in combinations of Fermi-Bose condensates. Besides opening a new regime for investigating superfluid hydrodynamics, our measurements provide new insight into superfluid behavior in confined geometries. We find strong evidence that  $T_c$  is fixed by the  $^3\text{He}$  in the largest pores and does not change significantly as considerable fractions of  $^4\text{He}$  are introduced into the system.

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