

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 ^3He - ^4He mixtures confined to aerogel. At mK temperatures, this inhomogeneous system exhibits simultaneous ^3He and ^4He superfluidity leading to two “slow modes” along with the conventional sound mode. We also infer the superfluidity of isolated bubbles of pure ^3He in a large ^4He concentration sample.

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Liquid ^4He (bosons) and ^3He (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 ^4He , 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 ^7Li or ^{23}Na atoms coexisting with a degenerate Fermi gas of fermionic ^6Li 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 ^4He and ^3He have attempted to produce a system in which both components are superfluid [5]. At milli-Kelvin temperatures, ^3He - ^4He mixtures with ^3He content in excess of 6% phase separate into a pure ^3He phase and a ^4He rich phase [6]. Estimates for the superfluid transition temperature, T_c , for ^3He dissolved in the ^4He rich phase range from 1 to 10 μK [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 ^3He - ^4He 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 ^3He - ^4He mixtures are introduced into an aerogel, the ^4He -rich component preferentially coats the surface of the strands, while the ^3He component fills the remaining voids [10,11]. Pure ^4He undergoes a sharp superfluid phase transition when confined to aerogel [12]. Pure ^3He and ^3He in contact with ^4He , in 98% open aerogel, also undergo well-defined transitions. Because the ^3He 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 ^3He or ^4He , 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 ^3He and ^4He 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 ^4He - ^3He 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 ^4He concentration in the aerogel is measured using a coaxial

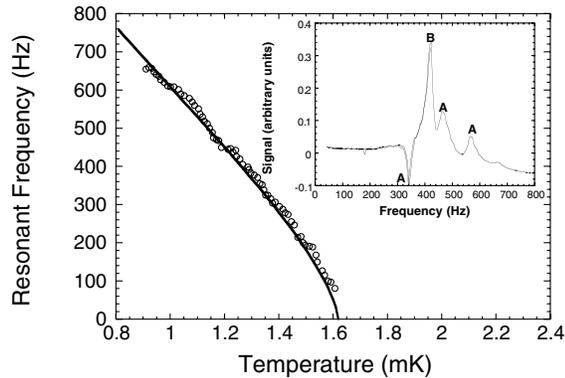


FIG. 1. The pure ^3He in aerogel slow mode resonant frequency as a function of temperature. The mode's frequency \Rightarrow 0 when the superfluid density vanishes at $T_c \approx 1.62$ mK. The solid line is the prediction from the model described below. Inset: A representative spectrum for ^3He in aerogel 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 ^3He melting curve thermometer.

The behavior of the superfluid sound modes in the cell was characterized by filling the aerogel with pure ^3He 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 ^3He in a 98% porosity aerogel at this pressure [9]. We interpret this resonance as arising from the slow mode of superfluid ^3He in aerogel.

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

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

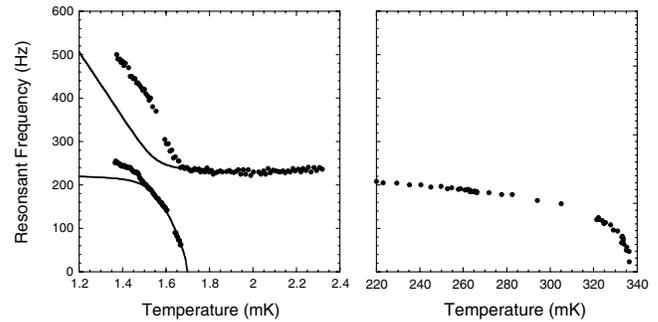


FIG. 2. The right-hand panel shows the resonant frequency for the high velocity slow mode in a mixture containing 10.5% ^4He . This mode vanishes at the ^4He superfluid T_c (337 mK). The left panel shows the continuation of this mode to lower temperatures together with the onset of the low velocity slow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

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

As the ^4He fraction in the aerogel was increased to 23%, 57%, and 71%, we observed qualitatively similar behavior to that seen in the 10.5% ^4He 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 ^3He T_c . We observe clear slow modes with an onset within $25 \mu\text{K}$ of the value for only a thin ^4He superfluid layer coating the aerogel. This suggests that the global value of T_c is determined mainly by

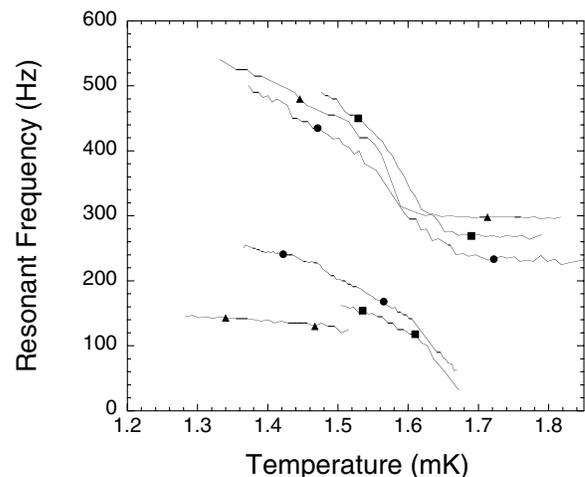


FIG. 3. These curves show the resonant frequency of both the slow modes in mixtures with 10.5% (circles), 23% (squares), and 71% (triangles) ^4He versus temperature.

the onset of superfluidity in the ^3He 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 ^4He , that captures the observed behavior. Consider a system consisting of phase separated incompressible ^3He and ^4He in an aerogel (with *constant* mass and number densities ρ_3 , n_3 and ρ_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 ^3He and ^4He 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 ^3He - ^4He interface follows the aerogel, in equilibrium, and that any drag between the ^3He and ^4He superfluids is negligible. The continuity equations for ^3He , ^4He , 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 ^3He and ^4He , 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 ^3He 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 ^4He 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 ^3He , 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 ^3He in aerogel are plotted in Fig. 1. In the mixture, there are two solutions: With decreasing temperature, one mode starts from zero at the ^4He T_c and is continuous through the ^3He T_c , while the other mode only propagates below the ^3He T_c . For values of ϕ_4 of a few percent, these speeds can be approximated as follows. The faster mode, continuous through the ^3He 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 ^3He and a ^3He - ^4He mixture with a volume fraction of liquid ^4He $\phi_4 = 0.06$ (corresponding to a ^4He concentration of 10.5% after subtracting the solid ^4He 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 ^4He concentration mixtures, we also investigate the superfluidity of isolated bubbles of ^3He in ^3He - ^4He mixtures in aerogel. Since the bulk solubility of ^3He in ^4He at 17.2 bars is approximately 8% [27], the ^3He rich phase fills only 4% of the free volume when a 89% ^4He 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 ^4He rich phase.

The left-hand panel of Fig. 4 shows the low temperature, low frequency acoustic spectrum for the 89% ^4He 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 ^3He phase does not percolate, there will be no hydrodynamic mass flow of the ^3He superfluid. However, the higher velocity slow mode is still sensitive to the ^3He 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 ^3He superfluid order parameter can develop in isolated coherence length sized droplets when confined by

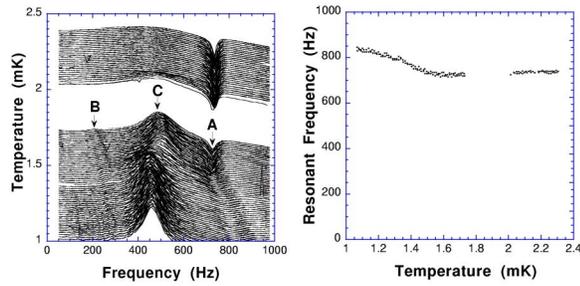


FIG. 4 (color online). The left panel shows the response of the microphone transducer, offset vertically by temperature. The resonance labeled A is the high velocity slow mode, the peak labeled B is a superfluid Helmholtz mode from the ^3He outside of the cell, and the resonance labeled C is the Helmholtz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

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

Confining ^3He and ^4He 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 ^4He 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 ^3He in the largest pores and does not change significantly as considerable fractions of ^4He are introduced into the system.

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 [23] The values of the ^3He superfluid density $\tilde{\rho}_{3s}$ at $p = 17.2$ bars with or without ^4He (suppressed down to $0.3\rho_3$ at $T = 0$) were taken from measurements in similar aerogels [19]. We take as a fitting parameter $c_a = 60$ m/s, similar to the measured value reported in [19]. For ^4He , the tortuosity factor $\alpha_4 \approx 10$ [11] was used to account for the momentum exchange between the ^4He superfluid fraction and the normal component, $\tilde{\rho}_{4s} = \phi_4\rho_4/\alpha_4$. The effective superfluid velocity is then defined as $\tilde{\mathbf{v}}_{4s} = \alpha_4(\mathbf{v}_{4s} - \mathbf{v}_n) + \mathbf{v}_n$, where \mathbf{v}_{4s} is the macroscopically averaged superfluid velocity.
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