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Journal of Non-Crystalline Solids 225 (1998) 205–209

JOURNAL OF NON-CRYSTALLINE SOLIDS

Suppression of ^{3}He superfluidity by aerogel

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Abstract

Experiments in which 98.2% porous aerogels exert a profound influence on the properties of superfluid ^{3}He are described. Superfluid transition temperature and superfluid density are reduced from their bulk values. Experiments use torsional oscillator techniques to examine the superfluid onset and temperature development with high precision in the mK temperature regime. Simulations are also discussed in the context of properties of ^{3}He. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Aerogel; Superfluid ^{3}He; Temperature; Density

1. Introduction

Superfluid ^{3}He is the only established example of p-wave pairing in nature [1,2]. It is also free of impurities since all other substances (with the exception of ^{4}He) solidify at the mK temperatures needed to attain superfluidity. The ^{4}He–^{4}He attraction is stronger than that of ^{4}He–^{3}He, so ^{3}He-rich phase is self-purifying at low temperatures. Thus, until the studies on ^{3}He in silica aerogel [3], there were no examples of p-wave superfluids in the presence of impurities.

The scattering of ^{3}He from a surface is a pair-breaking event and leads to the suppression of the superfluidity of ^{3}He within a coherence length [4]. The zero temperature coherence length is given by $\xi_0 = \hbar v_F / 2\pi k_B T_c$ and varies from 150 Å at high pressure to 800 Å at zero pressure. Here v_F is the Fermi velocity and T_c is the bulk superfluid transition temperature. The aerogel is made up of silica agglomerates whose characteristic size (30 Å diameter) is smaller than ξ_0; thus, the aerogel functions as an impurity with a role similar to that of magnetic scatterers in ordinary superconductors [5,6]. However, the exact relationship between ξ_0 and T_c^a, the transition temperature of ^{3}He in aerogel, is not well understood [7].

In this paper, we describe the results of three torsion pendulum experiments performed on ^{3}He in 98.2% porous aerogel. The experiments show that the superfluid density, ρ_S^a, and transition temperature, T_c^a are suppressed from their bulk values, ρ_s and T_c. Special features of each of the experiments are outlined. We start by briefly discussing simulations of the aerogel structure as it pertains to the behavior of ^{3}He.

2. Simulations

We 'grew' a computer generated silica aerogel using standard DLCA (diffusion limited cluster ag-

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PII S0022-3093(98)00042-8

gregation) algorithms [8]. The result for 98.2% porous aerogel is depicted in a 3D stereogram (Fig. 1). The structure reveals two important characteristics. The mean free path, λ, defined as the mean distance between collisions of a quasiparticle with silica is approximately 2200 Å and scales with the volume fraction of the aerogel occupied by silica, c, as λ $c^{-1.24}$. The mean distance from a random point within the void structure to the nearest silica is 90 Å and virtually any point within the void is less than 300 Å from the nearest silica. The absence of spherical cavities of radius > 300 Å implies that the Cooper pairs (size $> \xi_0$) that form the superfluid condensate, encompass one or more silica aggregates. Consequently, it is correct to conclude that the silica aerogel, on average, penetrates to the interior of the Cooper pairs. This rather abbreviated description is thought to be appropriate for the base catalyzed aerogels used in this study. No experiments have been carried out on aerogels with identical density but whose correlations (and consequently, λ) have been altered by a systematic variation of the pH during gelation.

3. Experimental

The aerogel used in the experiments was grown for us in stainless steel cups by N. Mulders and J. Yoon in M.H.W. Chan's laboratory at Penn State University. The aerogel was grown under basic conditions as described in Ref. [9]. The cups were then epoxied into a 'head' which formed the principal moment of inertia of a torsional pendulum. The torsion tube also functioned as the thermal link and fill line to connect the ^{3}He to a heat exchanger which could be cooled to below 0.4 mK. A schematic diagram of the torsional oscillator is shown in the inset to Fig. 2.

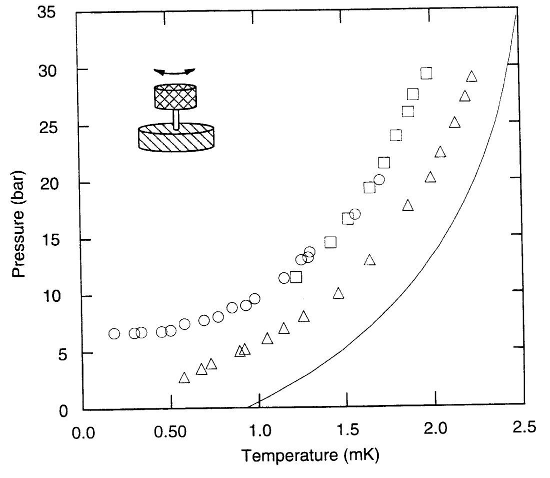

Fig. 2. The phase diagram of ^{3}He in 98.2% open aerogel. Solid line shows the T_c of bulk ^{3}He. $\triangle$ = data from cell A, $\bigcirc$ = cell B, $\square$ = cell C. Differences between the three cells probably reflect different pH during growth. Inset: we show a schematic of the torsion pendulum.

At low temperatures, the normal fluid is viscously coupled to the pendulum. The oscillator is driven at the resonant frequency of the torsional mode in a phase locked loop, and the period of motion is monitored. Upon entering the superfluid phase, the superfluid decouples from the pendulum as it has

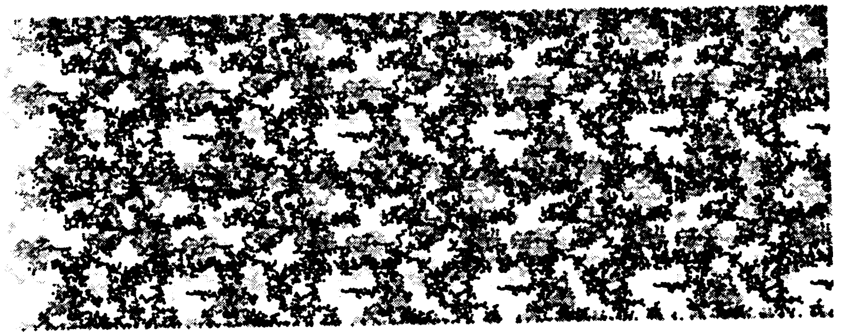

Fig. 1. The stereoscopic image of a computer-generated aerogel. To view the image, hold the image close and defocus your eyes. Then move the image 30–50 cm away. The dark spots should stand out and the gray ones recede from the surface. The view represents a 0.75 μm × 0.3 μm area × 0.15 μm deep section of aerogel.

zero viscosity, and this leads to a small decrease in the moment of inertia and the period of the pendulum. Temperatures were derived from the ^{3}He melting curve [10]. The fluid moment of inertia is 10^{-3} to 10^{-4} of the torsion head, yet the superfluid fraction, ρ_S^a/ρ, could be determined to better than 0.1% because of the high period stability.

4. Results

4.1. Cell A

The first experiments [3,11] showed that T_c^a was well defined with a width $< 0.2\% T_c^a$, suppressed below that of the bulk (see the data shown as △ in Fig. 2), and that the superfluid densities' temperature development was very different from that of the bulk. We found that ρ_S^a did not increase linearly (as in the bulk fluid) with reduced temperature, $(1 - T/T_c)$, but varied as $(1 - T/T_c^a)^{1.4}$. Further, ρ_S^a/ρ never exceeds 0.4 in contrast to that of the bulk where $\rho_s/\rho = 1$ at $T = 0$. We found that the period shift due to the superfluid became smaller as the pressure was lowered, accompanied by a reduction of T_c^a/T_c. However, ρ_S^a/ρ decreased faster than T_c^a/T_c so that the onset of superfluidity could not be tracked below 2.5 bar (0.6 mK), well above the minimum temperature of the refrigerator.

4.2. Cell B

The density of the aerogel that constituted sample B was nominally identical to that of sample A and was mounted on a similar torsion pendulum. However, a small disc shaped gap remained between the aerogel and the head which was filled with bulk fluid. This bulk sample (though only about 5% of the entire fluid contribution) gave rise to a period decrease that exceeded that of the fluid in the aerogel especially at low pressures (Fig. 3). In order to track the superfluid transition below about 0.9 mK, we maintained the refrigerator at a constant temperature and slowly changed the pressure and density of the ^{3}He. If we started from a low density where the entire fluid is normal, and added ^{3}He we found that the period of the pendulum increased linearly until the critical density, ρ_c at that temperature was exceeded [12]. Above ρ_c, the period fell below that of rigid body motion signaling the onset of superfluidity and the decoupling of the superfluid from the pendulum (Fig. 4). The collection of T_c^a vs. P is also plotted for cell as (○)B in Fig. 2.

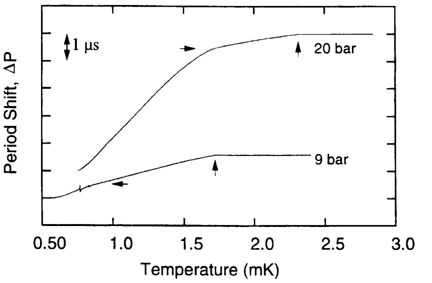

Fig. 3. The period vs. temperature for cell B. Vertical arrows designate T_c bulk, horizontal arrows T_c^a. The period shift from the ^{3}He in aerogel, proportional to ρ_S^a becomes progressively smaller at low pressures. The error bars are ≈ 0.1 ns, and are too small to indicate on the diagram.

The phase diagram of cell B is distinguished from that of cell A because the results from B can be extrapolated to show a $T = 0$ normal to superfluid transition. Such a transition between two zero entropy states is an example of a quantum phase transition (QPT) [13], where the fluctuations near the transition are quantum and not thermal in nature. Such a continuous transition can be crossed by tuning some parameter (in our case the density). There are numerous examples of 2D QPTs but 3D transitions are unusual. We note that structural (first order)

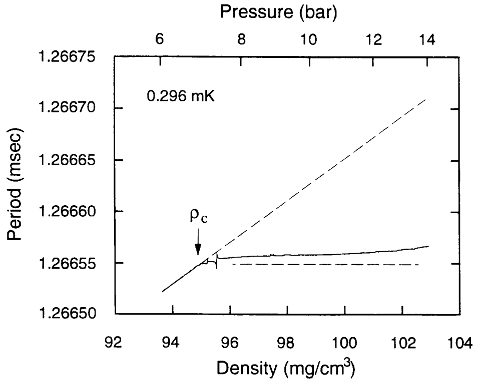

Fig. 4. Signal observed while pressurizing at $T = 0.296$ mK. ρ_c designates the critical density. Almost 90% of the fluid added above the critical density contributes to the superfluid state.

transitions do not fall into the category of QPTs since fluctuations do not play a significant role in describing the behavior at T_c.

The differences in the phase diagram of cell A and B can arise because of an extraordinary sensitivity to the density of the aerogel (controlled to better than 0.1%) or because of differences in the solution pH and thus of the dynamics of gelation. Differences in the pH can produce aerogels of a particular density that have different mass correlations [14] and in view of the relative sizes of ξ_0 and the silica agglomerates, it is likely that the suppression of T_c^a reflects the correlation as well as the density. Clearly, this will be the subject of a future study.

4.3. Cell C

This cell was specially configured for investigations of the properties of ^{3}He–^{4}He mixtures in aerogel. The aerogel has been shown to radically change the coexistence region of mixtures, and in particular the coexistence line is detached from the superfluid transition line [15]. This experiment has led to much theoretical work published in the literature.

Our interest is focused on the behavior of ^{3}He when the surfaces of the aerogel are coated with a ^{4}He-rich phase, i.e., when the ^{3}He–^{4}He mixture is phase separated. The aerogel was grown between the coaxial plates (consisting of a stainless steel screen) that made up a capacitor located in the head of the torsion pendulum. By monitoring the capacitance it is possible to assay the ^{4}He content of the mixture within the aerogel. Unfortunately, the presence of the capacitor produced acoustic resonances in the ^{3}He due to local inhomogeneity of the aerogel. Nevertheless, we were able to track T_c^a (($\square$) in Fig. 2) and ρ_s^a within the cell. This aerogel sample's T_c^a was close to that of cell B, consistent with the similarity of the gelation process used in the two cells.

Since ^{4}He is more tightly bound to surfaces by reason of its smaller zero motion and the van der Waals force, when ^{4}He is added to the ^{3}He, it first displaces the ^{3}He that is localized on the surface of the aerogel. This amount of ^{4}He (2%) raises the superfluid transition temperature by 70 μK (note for pure ^{3}He, T_c^a is depressed to 1.78 mK from T_c of 2.28 mK at 21.6 bar). We found that the addition of more ^{4}He progressively raises the superfluid transition temperature by a small amount. T_c^a increased from 1.85 mK to 1.90 mK as the ^{4}He content increased from 2% to 34%. We also found that the period shift signal became progressively smaller as ^{4}He was added (Fig. 5), and once we account for the contribution of a small bulk fluid signal, we find that the apparent ρ_s^a is reduced by a factor of 7 with 34% ^{4}He present.

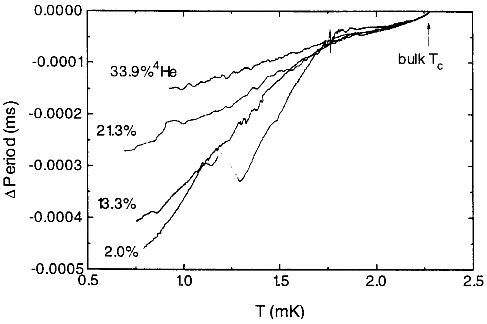

Fig. 5. The period signals from cell C with 2%, 13.3%, 21.3% and 33.9% ^{4}He contained in the aerogel. The transition temperature of the bulk superfluid (2.28 mK) is shown with the vertical arrow. The transition temperature of the ^{3}He within the aerogel falls between 1.85 and 1.90 mK depending on ^{4}He content. Samples with higher ^{4}He content show a smaller superfluid density while exhibiting a slightly enhanced T_c^a.

This result, a suppression of ρ_s^a while T_c^a increases, is counterintuitive. It is rather similar to the conductance signature of a Josephson coupled granular superconducting film, where T_c is set by that of the grains, and the resistivity is set by the coupling between grains. However, NMR studies on pure ^{3}He in aerogel showed that the superfluid transition was sharp [11]. Since NMR is a local probe, and our torsion pendulum probes global superfluidity, the sharp NMR features is critical in establishing that the superfluid is described by a global order parameter. This has been borne out in recent unpublished work at Manchester which shows that the ρ_s^a and NMR signatures coincide with one another. The role of the ^{4}He rich film in suppressing ρ_s^a while increasing T_c^a is then even more puzzling.

5. Conclusions

Studies indicate that the aerogel acts to suppress the superfluid density and the superfluid transition of

^{3}He in aerogel. Many new features appear in this system including the alteration of the power law development of the superfluid density, a quantum phase transition, and a novel coexistence diagram. The effect of a ^{4}He-rich film that coats the aerogel is much stronger than expected.

Acknowledgements

This work was supported by NSF grant # DMR-9424137.

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