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Scaling Results for Superfluid ^{3}He in 98% open Aerogel

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Abstract We present experimental observations of the suppressed superfluid transition temperature, T_{ca}, superfluid fraction, ρ_s/ρ and Leggett frequency of ^{3}He-B in aerogel, Ω_{Ba}. We determine T_{ca} from mass decoupling and the vanishing of the frequency shift away from the Larmor frequency in our different samples and different laboratories. We find that the suppressed transition temperature for ^{3}He in aerogel occurs at a sample dependent, but approximately pressure *independent*, length, $X = \xi_0(P)/\sqrt{1-T_{ca}/T_c}$, where T_c and $\xi_0(P)$, are the transition temperature and the pressure dependent zero temperature coherence length for bulk ^{3}He. T_{ca} also occurs at a pressure independent value of the Leggett frequency of bulk ^{3}He-B. Further, we find that when the superfluid fraction and square of the Leggett frequency are plotted against $T_{ca} - T$ (and *not* $(T_{ca} - T)/T_{ca}$), the results of each measurement nearly collapse on to a pressure independent but sample dependent plot, with no further scaling. When plotted on a log-log scale, both measurements exhibit power laws in the range 1.33-1.45.

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1 Introduction

More than a decade ago, experiments[1,2] revealed that the addition of a dilute impurity, silica aerogel, alters the properties of superfluid ^{3}He. The most obvious manifestation of these modifications is the suppression of the transition tempera-

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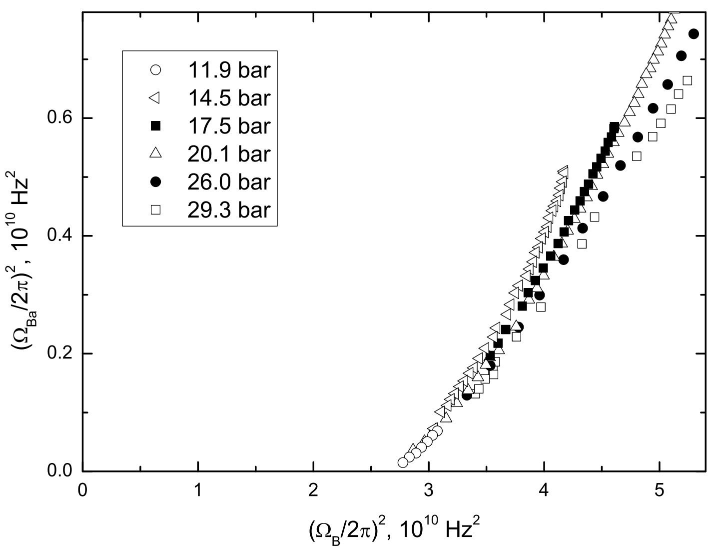

Fig. 1 The Leggett frequency observed for ^{3}He-B in 98.2% aerogel plotted against the Leggett frequency observed simultaneously in a bulk ^{3}He-B sample. All measured pressures show an onset of superfluidity of ^{3}He in aerogel (characterized by the frequency shift onset), at the *same* value of the bulk Leggett frequency. The Leggett frequency in the B-like phase was measured using the frequency shift for the textural defect [3], while the data for bulk ^{3}He were obtained in an additional bulk cell filled with a set of equally spaced plates orienting the texture of the order parameter (as described *e.g.* in Ref. [4]).

ture and the reduction of the superfluid fraction,ρ_s/ρ and its NMR analog in the B-like phase, the Leggett frequency Ω_B [3].

2 Results

Experiments were independently carried out at Cornell and the Kapitza Institute. We concentrate here on the scaling of ρ_s/ρ and Ω_{Ba} in the B-like phase of ^{3}He in aerogel and the suppression of superfluid transition temperature, T_{ca} in ^{3}He in aerogel.

We first discuss the power law scaling observed for both the development of the superfluid density and the square of the Leggett frequency in the B-like phase. Both these quantities in the bulk are characterized by the square of the superfluid order parameter, loosely characterizing the strength of the superfluidity. In Moscow, it was seen that the onset of the superfluid transition in the ^{3}He in aerogel always occurred at the same value of the bulk Leggett frequency (Fig.1). This feature seems to be universal, *i.e.* is valid also for aerogel samples with other densities (97.5% and 99.3%) and qualitatively agrees with the notion that the superfluidity in the disordered ^{3}He appears only once a certain pairing strength in the "clean" liquid is achieved.

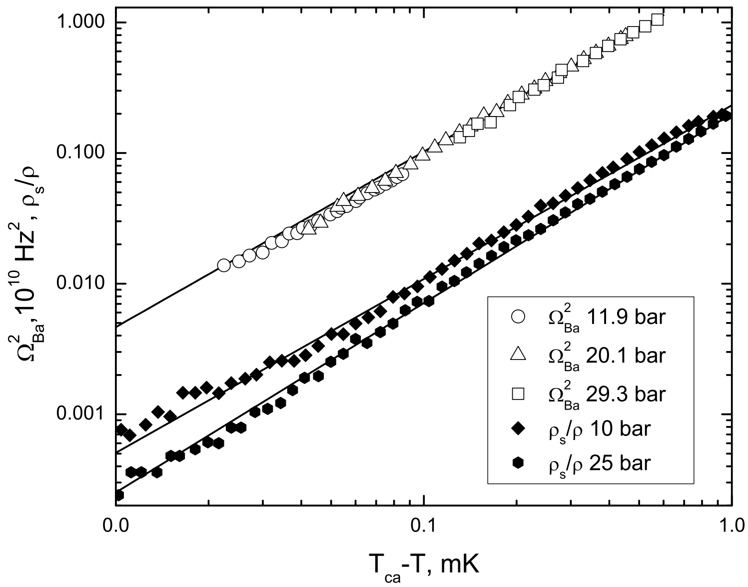

Fig. 2 The superfluid density ρ_s/ρ and Leggett frequency in the B-like phase Ω^2_{Ba}, plotted against the temperature below the onset of the superfluid transition $T_{ca} - T$ in mK. For clarity we show only two pressures for ρ_s/ρ, and three pressures for Ω^2_{Ba}. The near collapse of these is remarkable, as is the similarity of the power law behavior. We find the exponents for the temperature to be 1.38 for the NMR, 1.33 for the low pressure ρ_s/ρ, and 1.45 for the high pressure ρ_s/ρ.

It was also observed that the square of the Leggett frequency for the B phase of ^{3}He in aerogel, when plotted against the temperature below the suppressed superfluid transition temperature $(T_{ca} - T)$, exhibited a remarkable scaling: all the data from several different pressures collapse onto a single pressure independent plot. Further the power law exhibited by the data is 1.38, that is $\Omega^2_{Ba} = \mathrm{Constant} \cdot (\mathrm{T_{ca}} - \mathrm{T})^{1.38}$. The superfluid density in the B phase also showed a strikingly similar pressure independent behavior namely that ρ_s/ρ = A $(T_{ca} - T)^{\alpha}$, where (A,α) = (0.23,1.33) at low pressure and (A,α) = (0.20,1.45) at pressures above 15 bar. We note that the sample used in these experiments was warmed up to room temperature between the low pressure and high pressure set of measurements, so the difference in A and α for these sets may be due to some change of the sample properties (e.g. different amount of air or water adsorbed by aerogel strands). A selection of the data from the Cornell and Moscow groups are shown in Fig. 2.

These power laws are striking for several reasons. In the bulk liquid, the power law for both the square of the Leggett frequency and the superfluid density are linear and confined to the region close to T_c, in contrast to the broad region of power law behavior exhibited by the dirty system. The power laws of the two measurements are similar, and thus unlikely to arise out of coincidence. Further, in the bulk, there is no pressure independent scaling behavior for the Leggett frequency, and in the clean superfluid density, even the so called “bare” superfluid density

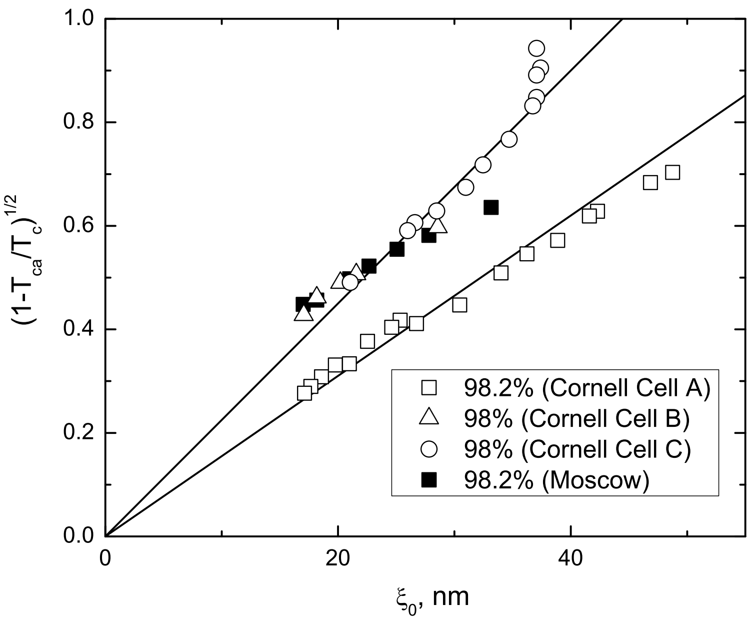

Fig. 3 The reduced transition temperature, $\sqrt{(1-T_{ca}/T_c)}$ at a variety of pressures for various 98% open aerogel samples measured in our laboratories, plotted against the zero temperature coherence length, ξ_0. The lines through the data correspond to slopes of 0.0155 nm^{-1} ($X = 65$ nm) and 0.0225 nm^{-1} ($X = 44$ nm).

(with Fermi liquid factors stripped out) shows a residual pressure dependence[5,6]. Thus the collapse of the data onto a nearly universal behavior is likely to be meaningful. Finally, we note that there is no precedent for a scaling that behaves as $(T_{ca} - T)$ instead of the usual reduced (dimensionless) temperature $(T_{ca} - T)/T_{ca}$.

The second area is the transition temperature suppression. It is natural to examine the onset of superfluidity for a length scale at which the transition occurs. The temperature dependent coherence length provides one such length scale. However, the complete expression for the coherence length variation with temperature was shown to *not* describe the observed suppressed transition temperature in aerogel T_{ca} correctly, in that T_{ca}/T_c did not occur at a fixed value of the coherence length[1]. In this paper we compare the observed variation to the so called "healing length" (really the Ginzburg-Landau expression for the temperature dependent coherence length), $\xi(T) = (7\zeta(3)/12)^{1/2}\xi_0(1-T/T_c)^{-1/2} = (0.838)\xi_0(1-T/T_c)^{-1/2}$, where T_c is the temperature of the bulk superfluid transition and $\xi_0 = (\hbar v_F)/(2\pi k_B T_c)$ is the zero temperature coherence length at the same pressure. We find that if we set $T = T_{ca}$, $\xi(T_{ca}, P) \approx X$, a constant. In Fig. 3, we show that this simple relation shows a reasonable ($\approx$ 10% agreement) with the experimentally determined T_c suppression. The values for $X = \xi_0(P)/\sqrt{1-T_{ca}/T_c}$ range from 65 nm to 44 nm, with the smaller value corresponding to the greater suppression seen in the newer aerogel samples (designated Cell B[7], Cell C[8] and Moscow[3] in Fig. 3). We note that the data at very low transition temperatures deviate from this expression possibly due to the different physics associated with the quantum phase transition[8]. We also note that the expression does not successfully account for the variation of transition temperature in more dilute aerogels. However, this simple relationship has proven invaluable in estimating the location of the transition, especially important in the case when the signal strength diminishes near T_c. On the face of it, the simplicity of the relation is compelling evidence that the healing length must shrink below some characteristic disorder length in the aerogel before superfluidity is expressed in the ^{3}He. A similar expression is developed in the so called "slab model"[9] though the relationship of a slab to the fractal structure of aerogel is not immediately obvious. A more compelling result is one which takes into account the distributed nature of the voids in the impurity, and this too successfully models the T_{ca} suppression[10].

3 Conclusions

The close parallels between the observed scaling behavior of NMR and superfluid density of dirty superfluid ^{3}He is striking evidence that the strength of the superfluid pairing is significantly modified from the bulk behavior. We note that the onset of superfluidity occurs at approximately pressure independent but sample dependent length scale. Whether this can be related to the observed onset of superfluidity at a particular (presumably sample dependent) value of the Leggett frequency is yet to be explored theoretically. Further, the observation of a very similar power law for the development of the superfluid density and the square of the Leggett frequency is also tantalizing, and it is remarkable that more than ten years after the first observation of dirty superfluidity the power law behavior, and collapse of these data onto nearly universal plots against $(T_{ca} - T)$ have not yet been understood theoretically. It is likely that further understanding will require the development of a relationship between the structural properties of aerogel to the experimental observations.

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