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Part S1 - Quantum Fluids and Solids: Liquid Helium

Contraction of aerogels by superfluid order

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We measured the thermal expansion dL/L of silica aerogels filled with liquid ^{4}He. A rapid contraction of the gel is observed at T_{c_0} slightly below T_λ at decreasing T. We found an additional expansion due to fountain pressure gradients. It suddendly decreases at a temperature $T_c(< T_{c_0})$. We interpret T_c as a critical temperature above which superfluid exists only in some regions.

1. INTRODUCTION

We present the first attempt to investigate the phenomena occuring at microscopic scales in the superfluid transition in aerogels : the confinement of the order parameter by the porous matrix has an energy cost that certainly depends upon gel deformation. Such an effect should induce an anomaly in the thermal expansion of the gel α_{gel} [1]. Owing to the very small bulk modulus B of silica aerogels the effect should be quite sizeable. Moreover, the existence of superfluid helium inside the aerogel is evidenced by the fact that temperature gradients developing in the gel induce fountain pressure gradients easily seen in the length of the sample. We have used a differential dilatometer of high resolution ($\sim$ 0.1 Å) described elsewhere [2].

1.1. Results for dL/L

In Fig. 1, we present the thermal expansion of three *neutrally reacted* aerogels of different densities. As shown in Fig. 1b hysteresis is observed at the lowest temperatures, even for $\partial T/\partial t$ as low as $2\mu K s^{-1}$. This is due to fountain pressure effect and will be discussed in the next section. A simple term of the form $dL/L|_{fountain} = -A\partial T/\partial t$ accounts for the existence of the hysteresis loop and was systematically substracted from the data.

For all samples, at increasing temperatures, the slope α_{gel} increases more and more rapidly to reach a maximum α_{max} at a temperature $T_{c_0} < T_\lambda$. α_{max}, T_{c_0}, and the width of the peak in α_{gel} depend strongly on the density of the gel. Far from T_{c_0}, the general shape of the dL/L curves resembles to that of the density of bulk liquid helium and the expansion of the three samples are comparable in magnitude. The explanation of this is the expansion of each silica particles by the change in surface tension due to the change in the density of helium. The bulk modulus involved there is that of bulk silica, explaining the similarity for the different samples.

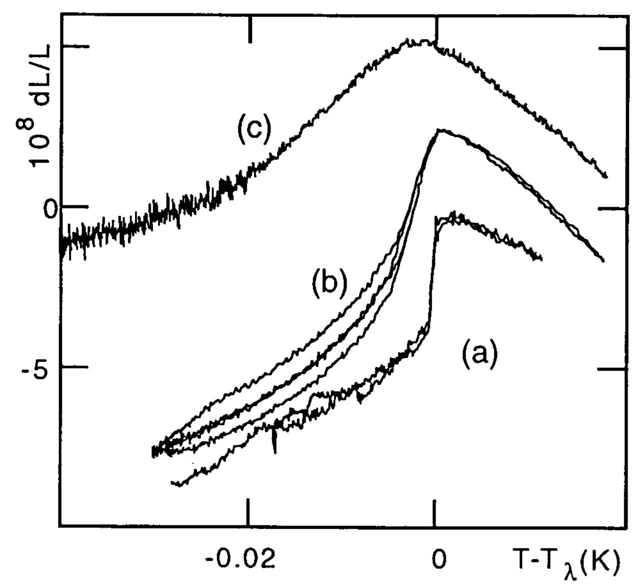

Figure 1 : Length change of three N-aerogels filled with liquid He. ρ =(a) 0.16, (b) 0.23, (c) 0.36 g/cm^3. For (b) the raw data is shown before the correction for fountain pressure.

This has to be contrasted with the expansion close to T_{c_0} which strongly depends on the gel density. This dependance arises because the large length scales of the gels are involved in this temperature range, involving the bulk modulus of the gel [2]. The order of magnitude of α_{max} compares favorably with the estimate given in [1], involving the confinement of the order parameter by the porous skeletton and the elasticity of the latter. An important point arises concerning the sign of α_{max} : the arguments given in [1] imply a negative α_{max}. The reason why the order parameter contracts the gel remains to be explained.

1.2. Fountain pressure

During the temperature sweep, we applied a low frequency AC heat power $Q(t)$ to induce an oscillating response ΔL due to the fountain effect. We used a frequency of 10^{-2} Hz and an amplitude Q_0 typically 0.1 to 5 mW. The amplitudes ΔL_0 (in phase with $Q(t)$) and ΔT_0 (out of phase) are proportional to Q_0 over the full range of Q_0. We find $\delta(T) = \Delta L_0/\Delta T_0$ increasing slowly with increasing T and dropping suddenly at a temperature T_c ($< T_{c_0}$) above which it vanishes progressively as T crosses over T_{c_0} (Fig. 2). $T_\lambda - T_c = 0.7$ mK, 5.3 mK, 21 mK for samples (a), (b), and (c) respectively.

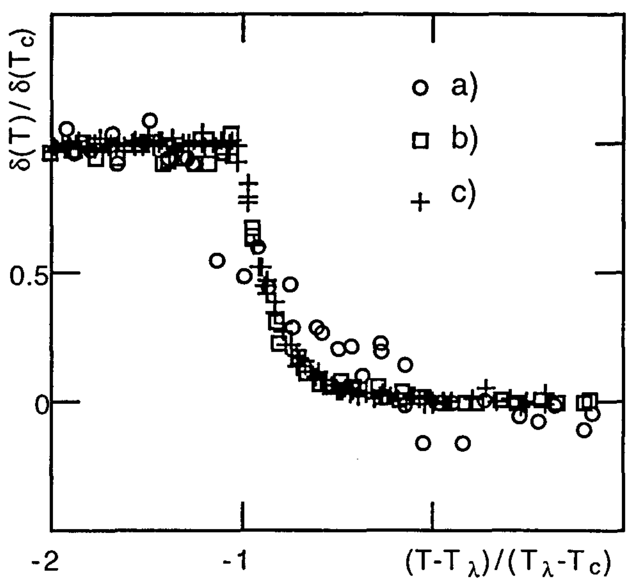

Figure 2 : $\delta(T) = \Delta L_0/\Delta T_0$ is plotted relatively to its value at T_c, for samples of Fig. 1.

Obviously T_c is the temperature above which the superfluid component is only present in some regions of the sample. Probably, only below T_c, superfluid provides a connected path throughout the sample. Thus T_c should be the transition temperature measured in torsional oscillator and fourth sound experiments. The existence of a finite ρ_S above T_c observed in previous measurements [3, 4, 5] was interpreted in terms of the presence of defects in the gels. We do not believe that this is the case for our gels since the decrease of $\delta(T) = \Delta L_0/\Delta T_0$ above T_c is quite reproducible from one gel to another as shown in Fig. 2.

2. CONCLUSIONS

The macroscopic transition observed in torsional oscillator experiments [6] is reflected in our experiment by the sudden decrease of the thermal superflow at T_c. However, we obviously cannot ignore the existence of superfluid above T_c and its large effect on dL/L for $T_c < T < T_\lambda$.

The most spectacular effect in the expansion of the gel arises between T_c and T_λ where the expansion is positive and becomes very high for the lightest samples ($\geq 5 \times 10^{-5}$/K). Outside this temperature region, the expansion of the gel is dominated by the Van der Waals type interaction between helium and the silica particles.

We now suggest a possible scenario for the change in critical indices observed in aerogels, compatible with our observations. The main caracteristic of aerogel-like samples is the heterogeneity at any length scale. This might induce a significant spread of local critical temperature for the helium in the sample. Above some temperature T_c, superfluid regions might be present in the sample, but not connected at macroscopic length scales. T_c would then be a percolation transition for the superfluid regions. This picture, allthought very crude is some restatement of the conclusion of Weinrib and Halperin [7].

We have two experimental facts supporting this conclusion : (i) existence of superfluid heat transport above T_c; (ii) the largest effect on the gel length occurs above T_c; implying that part of the phenomena occur above T_c.

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