Characterization of fractals with an adsorbed superfluid film

A.I. Golov* , I.B. Berkutov1, S. Babuin, D.J. Cousins

Department of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, UK

Abstract

The tortuosity of a capillary-condensed film of superfluid 4He adsorbed on 91%-porous silica aerogel has been measured, with transverse sound, as a function of helium coverage. Complementary data from 4He adsorption isotherms and small-angle X-ray scattering have also been used for substrate characterization. The tortuosity is found to be roughly inversely proportional to the volume fraction of the liquid phase of helium.

Keywords: Superfluidity; Aerogel; Tortuosity; Fractal

1. Introduction

We report an attempt to develop a new tool to gain information on the microscopic structure of porous materials. The idea is to measure how the tortuosity of an adsorbed liquid film changes with the liquid volume fraction. Thin films follow all irregularities of the tortuous substrate, while with thicker films the short length scale irregularities are shunted by the liquid capillary condensed in small pores. The scaling of the tortuosity with the size of the biggest filled pore or volume of adsorbed liquid could work as an independent fractal characteristic of the material.

We studied a sample of 91%-porous silica aerogel made by Airglass, Sweden. Small angle X-ray scattering revealed a range of mass fractal correlations between the scattering vectors \( q = 0.02 \) and \( 0.06 \) \( \text{Å}^{-1} \) (i.e. between length scales of order \( \sim \pi/q = 50 \) and 150 \( \text{Å} \)) with the fractal dimension of 2.0.

The tortuosity, \( \alpha \), is the geometric factor in the solution of the equation for flow of liquid along a tortuous flow path [1,2]. For superfluid 4He in porous materials it is usually expressed by the “drag factor” [3], \( \chi = 1 - \alpha^{-1} \), and can be used to characterize the morphology of capillary-condensed films [4].

2. Experimental results and discussion

Transverse sound resonance in a thin slab of aerogel [5] was used to extract the overall coupled density of helium \( \rho_s(T) \) from the resonant frequency \( \nu(T) \). All adsorbed helium is divided into two parts: the inert solid layer of overall density \( \rho_0 = 0.010 \) g/cm\(^3\) (using the “critical coverage” value of \( n_c = 36 \) µmol/m\(^2\) for 91%-porous aerogel [6]) and the liquid part with overall

\[ \delta \mu \equiv \mu_b - \mu = -k_B T \ln \left( \frac{p}{p_0} \right), \]

\[ r(p) = -\frac{2\sigma v_4}{k_B T \ln(p/p_0)}. \]
density \( \rho_l = \phi \rho_b \), where \( \phi \) is the volume fraction of the liquid part and \( \rho_b = 0.146 \, g/cm^3 \) is the bulk 4He density. At \( T = 2.2 \, K \) all the helium mass is coupled to the oscillating aerogel, while at \( T = 0.5 \, K \) all the liquid part is superfluid and coupled to the aerogel only through the tortuosity of the film. Hence

\[
\alpha = \left(1 - \frac{\rho_l(0.5 \, K) - \rho_0}{\rho_l(2.2 \, K) - \rho_0}\right)^{-1},
\]

\[
\phi = \frac{\rho_c(2.2 \, K) - \rho_0}{\rho_b}.
\]

In Fig. 2 we plot our values of tortuosity \( \alpha(\phi) \) for the capillary-condensed regime when \( \rho_c(2.2 \, K) > 0.025 \, g/cm^3 \) (i.e. for \( \phi > 0.1 \)) as well as some of the data obtained by Dolesi et al. [7] for 4He at \( T = 1.25 \, K \) in 93.5%-porous silica aerogel from the same manufacturer. The latter were re-analyzed to account for the inert layer using the value \( \rho_0 = 0.007 \, g/cm^3 \) obtained from our value of 0.010 g/cm^3 by scaling with the aerogel density. Both data sets are in good agreement and follow the law \( \alpha = \phi^{-\varepsilon} \) with \( \varepsilon \approx 1.16 \). For comparison, the results for 4He saturated in non-fractal porous media (fused-glass beads [2] and packed powders [8]) of various porosities are shown too. It is clear that the tortuosity of films on aerogels differs markedly from that of helium in non-fractal porous media.

The solid lines in Fig. 2 show the calculated values of \( \alpha \) for liquid in a model medium constructed by nested infinitesimal increments of density of self-similar spheres or needles [1] predicting the exponents between \( \varepsilon = 1/2 \) and \( \varepsilon = 1 \). Other theories for the density dependence of the tortuosity or conductivity of random or fractal networks exist, usually predicting \( \varepsilon \geq 1 \). However, much smaller substrate-dependent values of \( \varepsilon \) for the tortuosity of a capillary-condensed film on surface fractals have been predicted as well [9,10]. We would like to know whether or not the power law with the \( \varepsilon \approx 1.16 \) is universal for different types of aerogel or other porous mass fractals. Further experiments and model calculations are under way.

Acknowledgements

The research was supported by EPSRC grants GR/N07752, GR/N35113 and CLRC-38020, and University of Manchester grant AB021NP.

References