QUANTUM SYSTEMS

Excitations of superfluid helium in porous media

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The elementary excitations of superfluid ^{4}He, characterised by the phonon-roton dispersion curve, have been studied in great detail over the last forty years since the first observation of the roton in a pioneering neutron-scattering experiment in Stockholm in 1957 [1]. The interest today is turning towards the effect of disorder and confinement on these excitations, when e.g. helium is immersed in porous media. The key word is here “dirty bosons”. We have studied the microscopic dynamics of superfluid ^{4}He in porous media using the IN12 and IN6 spectrometers at the ILL. These measurements suggest that the modifications of the macroscopic properties (specific heat, superfluid fraction) are related to the existence of two-dimensional (2D) excitations rather than to modifications of the three-dimensional (3D) bulk excitations, such as the roton.

The porous media used in this investigation are aerogel and Vycor. Aerogel is a highly tenuous structure of irregularly connected silica (SiO_2) strands with a large distribution of pore sizes and porosities ranging from 85 to 99.5%. Vycor can be considered as a network of worm-like channels in silica with a rather well defined diameter of about 70 Å and a porosity of about 30%. When superfluid helium is immersed in these media, the macroscopic properties are modified due to confinement and/or disorder [2]. In aerogel, the superfluid transition temperature T_s is lowered from that of the bulk (Tl = 2.17 K) by only a few mK, while the critical exponent   in the expression for the temperature dependence of the superfluid fraction $_s(T)/ \ = (1-T/T_s)$ is modified, indicating a possible change in the universality class. In Vycor on the other hand, T_s is lowered to 1.95 K, while   is the same as in the bulk.

Our measurements on 4He in aerogel show that the 3D bulk-like excitations are the same as in bulk superfluid helium.
In particular, the temperature dependence of the roton energy (Fig. 1) and the roton width is the same in aerogel as in bulk. There are no observable deviations from the bulk behaviour that

could explain the differences in the macroscopic properties.

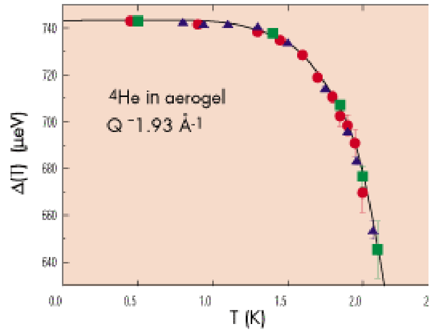

Figure 1: Temperature dependence of the roton energy measured for different aerogels on IN12 (red and green) and IN6 (blue). No deviations are found from bulk 4He (line).

However, additional intensity is observed slightly below the roton energy, as illustrated in Fig. 2 for different filling fractions. The intensity of this low-energy mode saturates quite rapidly with filling fraction, in contrast to the bulk mode whose intensity increases linearly with filling. This suggests that the low-energy mode is propagating in the first liquid layers near the substrate (the two first layers are solid).

Similar excitations have been observed in thin films of helium on graphite surfaces [3,4], but the present result is the first observation of layer modes in aerogel. The dispersion of the layer mode is similar to that of the bulk roton, as shown in the inset of Fig. 2, but with a lower energy. Layer modes are also observed in our measurements on helium in fully filled Vycor. The energies of these modes are smaller than that of the bulk roton, and consistent with the observed specific heat and $_s$(T)/ at low temperatures. The 3D phonon-roton excitations are very similar to bulk helium, as shown in Fig. 3, with the same energy and width, and the same temperature dependence. With increasing temperature, the intensity of the main (roton) peak decreases. In bulk liquid ^{4}He, the intensity of the roton scales approximately with the superfluid fraction $_s$(T)/ and disappears at T = 2.17 K [5], where $_s$/ = 0. Above Tl, only a very broad contribution is seen. We find that the roton intensity of helium in Vycor does not scale with $_s$/ in Vycor. Specifically, there is a clear peak at T = 1.99 K, which is above the superfluid transition temperature T_s = 1.95 K in Vycor. The peak has disappeared by T = 2.3 K. Theoretical work [6] suggests that the roton intensity should scale with the Bose condensate fraction n_0(T) rather than $_s$(T).

The results in Vycor suggest that if the intensity scales with n0(T), then the Bose-Einstein condensation temperature (BEC) T_{BEC} must lie above the superfluid transition temperature T_s in Vycor. In other words, T_s and T_{BEC} may be separated in Vycor.

There are sound physical reasons to believe that such a separation due to disorder is possible.

Neutron scattering measurements of the condense fraction of helium in Vycor are needed to clarify this intriguing possibility.

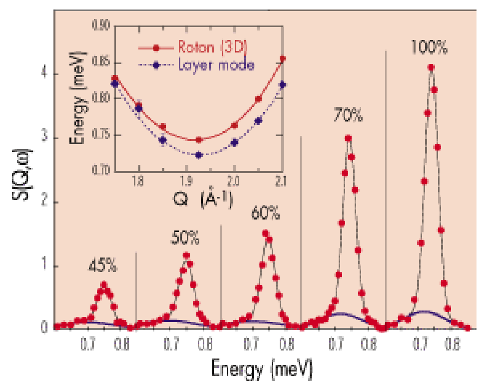

Figure 2: Dynamical structure-factor for superfluid 4He in 87% porous aerogel at T = 0.5 K for different percentage fillings measured on IN12. The thick blue line shows the 2D layer mode. The inset shows the energy of the bulk 3D roton and the 2D layer mode.

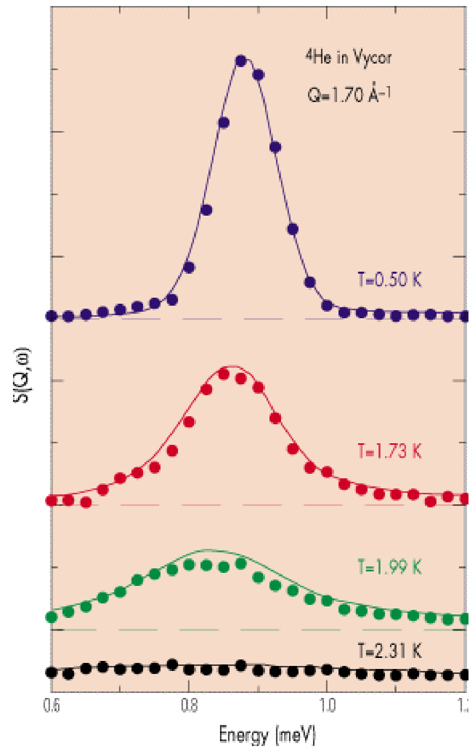

Figure 3: Comparison of the dynamical structure factor of superfluid ^{4}He in Vycor (filled corcles) with bulk helium (lines) at different temperatures measured on IN6 for a wave-vector slightly smaller than the roton wave-vector.

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[1] H. Palevsky et al., Phys. Rev. 108 (1957) 1346. [2] J. D. Reppy, J. Low Temp. Phys. 87 (1992) 205. [3] W. Thomlinson et al., Phys. Rev. Lett. 44 (1980) 266. [4] H. J. Lauter et al., Phys. Rev. Lett. 68 (1992) 2484; J. Low Temp. Phys. 87 (1992) 425. [5] A. D. B. Woods and E.C. Svensson, Phys. Rev. Lett. 41 (1978) 974. [6] H. R. Glyde and A. Griffin, Phys. Rev. Lett. 65 (1990) 1454.
