The Interfacial Thermal Resistance between Bulk Superfluid ^{3}He and Liquid ^{3}He in Aerogel at Ultralow Temperatures

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Abstract

We present the first measurements of the thermal boundary resistance of the interface between the two different liquid phases; bulk superfluid and liquid confined in aerogel. We set up a heat flow along a liquid-filled tube containing a plug of 98% aerogel, and measure the temperature at the two ends. At the lowest temperatures the resistance is dominated by the boundary resistance at the aerogel surfaces and is unaffected by the superfluid transition of the ^{3}He in the aerogel. Whereas in conventional Kapitza resistance the boundary conductance is limited by *acoustic* mismatch, here the conductance is limited by an *energy* mismatch, since quasiparticles with energies above the bulk B-phase gap may freely cross the interface, while those with lower energies are confined to the aerogel.

Key words: superfluid ^{3}He; thermal boundary resistance; aerogel

We can exploit the changes induced in superfluid ^{3}He by the impurity scattering when the liquid is immersed in low-density aerogel glass, since the confined liquid can be considered virtually as a 'new' phase of the superfluid. A great advantage is that we immediately have an aerogel-confined/bulk phase interface at any free aerogel surface in the liquid with discontinuities in the gap, quasiparticle mean free path, etc. The interface is normal-to-superfluid or superfluid-to-superfluid depending on pressure, since the liquid confined in the aerogel only becomes superfluid at the higher pressures. We present here the first measurements of the thermal boundary resistance of the interface between the bulk superfluid and liquid ^{3}He confined in 98% aerogel glass. We find that at ultralow temperatures the boundary resistance increases exponentially with falling temperature corresponding to the radiation limit for ballistic quasiparticles. The resistance arises from the energy mismatch of quasiparticles across the bulk/aerogel interface. The minimum quasiparticle energy in the bulk B-phase is set by the bulk energy gap Δ_B whereas in the aerogel it is zero for normal liquid or equal to the much suppressed energy gap Δ_a of the dirty superfluid. Quasiparticles with energies above the bulk energy gap are able to propagate freely across the interface whereas quasiparticles with lower energies are confined to the aerogel. Heat may only be transferred from the aerogel to the bulk by the radiation of the higher energy quasiparticles. This may be considered as a form of quasiparticle evaporation.

The experimental arrangement, shown inset in figure 1, was designed for measuring the thermal conductivity of aerogel-confined ^{3}He. A cylindrical aerogel sample of diameter 1.9 mm and length 3.8 mm is fixed tightly inside a thin tube of cigarette paper. A small amount of Stycast 2651 glue, applied to the outer surface of the tube, penetrates the paper to form a seal between the aerogel and the tube with no noticeable effect on the aerogel sample. This tube forms the orifice of a black-body radiator[1] consisting of a stycast impregnated paper box containing two vibrating wire resonators[2], a heater wire and a thermometer wire[3]. The heater wire is formed from a 3 mm semicircular loop of 13 μm NbTi wire, while the thermometer wire consists of a similar loop of 4.5 μm NbTi wire. A further

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thermometer is located outside the radiator. The experiment is placed in a Lancaster style nuclear cooling stage similar to that of ref. [4]. We make the measurements by applying heat Q to the radiator while measuring the temperature on each side of the aerogel. The measurements are made with powers low enough that the heater wire is never driven above its pair-breaking critical velocity, which would otherwise interfere with the thermometry. At such low powers, the temperature rise outside the radiator is too small to detect. Since the temperature change within the radiator ΔT is also very small, we infer the total conductance through the aerogel tube from the relation $K = Q/\Delta T$.

In figure 1 we plot the measured conductance K as a function of the mean temperature within the radiator for several pressures. For normal ^{3}He confined in aerogel we assume that the conductivity is given by the simple kinetic theory expression[5] $k = \frac{1}{3} C_v v_F \lambda$, where C_v is the heat capacity per unit volume, v_F is the Fermi velocity and λ is the aerogel-limited quasiparticle mean free path. The solid lines in the figure correspond to this expression with the appropriate normal state quantities [6], and a pressure independent mean free path $\lambda = 90\,\mathrm{nm}$. The thermal conductivity data will be discussed in greater detail elsewhere. Here, however, we simply point out that at the higher temperatures and for pressures up to 5 bar the data fit well to the normal state behaviour. For higher pressures the data fall below this prediction, indicating that the aerogel-confined ^{3}He is superfluid.

In the present context the significant aspect of the measured K is the rapid fall at the lowest temperatures. This arises from the extra boundary resistance. The dashed curves represent the conductance calculated from the simple theory outlined below.

To describe the boundary resistance, we represent the liquid ^{3}He in the aerogel by a volume of normal fluid (or superfluid) with zero (or small) energy gap. Thermalisation within the aerogel takes place efficiently owing to the short quasiparticle mean free paths, whereas thermalisation in the bulk superfluid presumably occurs only at the walls of the container at these low temperatures. While quasiparticles with energies greater than the bulk gap are able to pass freely across the interface, there must appear a finite temperature discontinuity at the interface whenever there is a net heat current. The power incident on a surface per unit area from a thermal bath of quasiparticles in the B-phase is given by $Q = \frac{1}{2}\int_{\Delta_B}^{\infty} f(E,T) g(E) v_g(E) dE$ where $f(E,T)$, $g(E)$ and $v_g(E)$ are the Fermi function, the quasiparticle density of states and the group velocity respectively. The factor of 1/2 comes from the angular integration and includes both particle and hole contributions. The boundary conductance per unit area (dQ/dT) is then given by

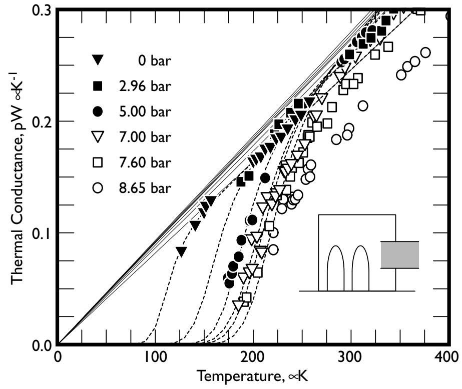

Fig. 1. The thermal conductivity of a cylinder of superfluid ^{3}He-B interrupted by a 98% aerogel plug (as shown in the inset). The fall at low temperatures is caused by the boundary resistance at the interfaces. Solid lines give the predictions for normal ^{3}He. Dashed lines include the boundary resistances.

$$K = \frac{1}{2}\, g(E_F)\, v_F\, k^2 \, \frac{\mathrm{d}}{\mathrm{d}T} \left(T^2 \int\limits_{\Delta_B/kT}^{\infty} \frac{x}{(e^x+1)}\, \mathrm{d}x \right)$$

The boundary resistances at the ends of the aerogel plug are in series with the ^{3}He thermal resistance across the aerogel sample. The total conductance is thus obtained using the normal state expression for the aerogel conductance and including both the bulk-aerogel and aerogel-bulk interfacial resistances. This is shown by the dashed lines in figure 1. As can be seen, the agreement (with no fitting parameters) is very good. We have assumed in all cases here that the ^{3}He in the aerogel is normal. This is not the case at the higher pressures and we see that at the higher temperatures these data lie below the dashed curves since the aerogel-confined liquid is superfluid.

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