

A Geometry Dependent Thermal Resistance Between a Saturated Dilute $^3\text{He} - ^4\text{He}$ Solution and Sintered Silver Powder

D.J.Cousins, A.M.Guénault, G.R.Pickett, P.Thibault, R.P.Turner

*School of Physics and Chemistry
Lancaster University, Lancaster LA1-4YB, United Kingdom*

E.N.Smith

*Cornell Microkelvin Laboratory,
Cornell University, Ithaca NY, 14853*

C.Bäuerle, Yu.M.Bunkov, S.N.Fisher, H.Godfrin

*Centre de Recherches sur les Très Basses Températures
CNRS, BP 166, 38042, Grenoble, France*

*We present direct measurements of the thermal resistance between a saturated dilute $^3\text{He} - ^4\text{He}$ solution and sintered silver powder between 5 and 150mK. Measurements obtained using different sinter geometries allow us to distinguish the contribution due to the thermal boundary resistance from that of the size-limited thermal resistance of the $^3\text{He} - ^4\text{He}$ solution within the pores of the sinter. The thermal boundary resistance per inverse unit volume is found to vary as T^{-3} and is insensitive to the sinter particle size.
PACS number: 67.60.Fp*

1. INTRODUCTION

The thermal resistance between sintered metals and the helium liquids is an area of obvious importance to the experimentalist who is continually wanting lower working temperatures for dilution refrigerators and for studying the properties of quantum fluids at ultra low temperatures. Un-

fortunately it seems that different measurements do not in general produce consistent results. The theoretical stance remains unclear.

During the late 1970's, the general consensus amongst experimentalists was that the thermal resistance between dilute ^3He - ^4He solutions and sintered metals varied as T^{-3} at low (milliKelvin) temperatures, see, for example, the review by Harrison.¹ Such a temperature dependence suggests a phonon mechanism for the heat transport. More recent measurements² below 10mK suggest that the resistance actually varies as T^{-2} .

Here, we present a series of measurements of the thermal boundary resistance between a saturated dilute ^3He - ^4He solution and sintered silver powder over a wide range of temperatures spanning 5mK to 150mK. The measurements were made using samples of sinter with different geometries and particle sizes. We find that the thermal resistance is geometry dependent if the thickness of the sinter exceeds a temperature dependent length scale. We attribute this length scale to the effects of the thermal resistance of the mixture within the pores of the sinter. At sufficiently low temperatures and for sufficiently thin sinters, the true thermal boundary resistance dominates. We find this to vary as T^{-3} down to the lowest temperature of our measurements.

2. EXPERIMENTAL

The first measurements were made in Lancaster and can be found also in ref.2. Four sintered silver specimens were made using Silbest C8 (nominally 800Å) powder.⁴ The sinters were made in the form of 10mm squares on carefully annealed 1mm thick silver plates. Attached to each silver plate are two 1mm silver wires. Different amounts of powder were used for each of the four sintered squares. The masses chosen were 0.111, 0.2666, 0.4822, and 1.007g yielding, respectively, thicknesses of 0.187, 0.389, 0.743, and 1.685mm, giving an average packing fraction of 56%. Great care was taken to ensure the sinters were made in an identical manner. The surface areas were measured by the BET method yielding $2\text{m}^2/\text{g}$ for each sample.

The four sintered silver specimens together with a fifth silver substrate (identical to the other four but without any sinter) are passed through a detachable base plate of the dilution refrigerator.⁵ To each specimen, a carbon resistance thermometer and an ohmic heater are attached to the ends of different silver legs. The whole assembly is then fitted to the mixing chamber.

The carbon resistors are first calibrated against a vibrating wire, located in the dilute phase of the mixing chamber, using the dilute solution viscosity data of de Waele et al.⁶ A measurement is made by heating one of the spec-

imens while monitoring the five carbon resistors. After the thermometers have stabilised, the thermal resistance is calculated from the small temperature difference between the heated specimen and the non-heated specimens. The procedure is repeated for the remaining specimens and then the mixing chamber temperature is adjusted for the next set of measurements. Since the temperatures of all the non-heated specimens were measured, we could check that the measuring process did not produce any measurable temperature gradients in the surrounding mixture.

Measurements of the thermal resistance between sintered DC10 ($1.5\mu\text{m}$) silver powder⁷ and a saturated dilute ^3He - ^4He solution were performed in Grenoble. The sample sinter was the outermost sinter of a stack of five identical sinters. The sinters were made using a more usual technique. A 99.99% pure 19mm by 37mm by 0.1mm silver foil was spot welded along two sides to two 1mm silver wire legs. Approximately 7.5g of the $1.5\mu\text{m}$ silver powder was sintered to each side of the foil yielding a slab of dimensions 19.6mm by 37mm by 4.4mm ($\sim 2.1\text{mm}$ of sinter on either side of the foil) with a packing fraction of 45%. The surface area of this sinter was measured, using the BET method, to be $0.34\text{m}^2/\text{g}$. The sinters are passed through the base plate of the mixing chamber in a similar manner as described for the sinters used in Lancaster. To the outermost sinter of the stack, to be used for the boundary resistance measurements, a CMN thermometer and a calibrated carbon resistance thermometer are attached to one of the silver legs. An ohmic heater is attached to the other leg. Two more calibrated carbon resistance thermometers are attached to the legs of the neighboring sinter in the stack, and a fourth carbon resistor is located directly in the mixing chamber in the open volume surrounding the sinter stack. The carbon resistance thermometers were previously calibrated against an NBS (768) fixed point device and a Germanium resistance thermometer.

The measurements proceed in a similar manner to those described above. Heat is supplied to the outermost sinter while monitoring all of the thermometers. In the absence of a temperature gradient between the non-heated neighbouring sinter and the surrounding free volume, the thermal resistance is found from the small excess temperature of the heated sinter.

3. RESULTS AND DISCUSSION

The results of the measurements are shown in the figure (we should emphasize that this is the resistance for each sinter without any normalization). The high temperature data obtained for the $1.5\mu\text{m}$ powder are shown with error bars which correspond to a thermal gradient between the sinter stack and the mixing chamber free volume. This arose because the sinters

were quite closely packed, separated by only $\sim 0.5\text{mm}$. However, the thermal gradient at low temperatures was negligible, yielding reliable results for the (T^{-3}) thermal resistance. The measurements made in Lancaster, with a more open geometry, had no measurable thermal gradients in the free volume surrounding the sinters. The results for the different sinter thicknesses clearly show evidence for a temperature dependent length scale. At high temperatures the thermal resistances for all four sinters are essentially the same, and follow an approximate $T^{-1.5}$ dependence. As the temperature is decreased, thicker sinters successively peel off from the common high temperature behaviour to follow a T^{-3} dependence.

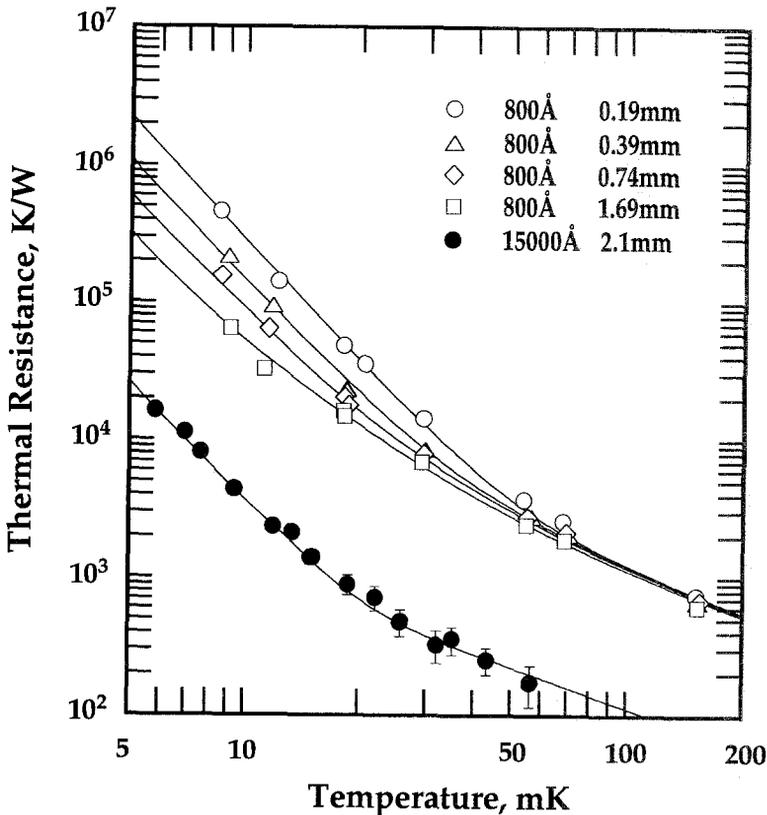


Fig. 1. The thermal resistance between a series of silver sinters with different geometries and particle sizes, as a function of temperature. The lengths (in mm) refer to the sinter thicknesses. The solid lines are calculated from the model described in the text.

We interpret this behaviour as the combined effect of the boundary resistance and the resistance of the mixture within pores of the sinter. These two resistances combine in a series-parallel arrangement. At high temperatures the resistance of the mixture within the sinter is comparatively large. The supplied heat will flow mainly within the sinter until a distance Λ is reached from the interface between the bulk sinter and the bulk mixture. There is a net heat flow from solid to liquid only within this distance where the thermal path from the liquid within the pores to the open volume is not too large compared to that of the sinter to the liquid.

The series-parallel resistance, in one dimension, is given by

$$R = A^{-1} \sqrt{R_K \rho_M} \coth(l/\Lambda) \quad (1)$$

where

$$\Lambda = \sqrt{R_K / \rho_M} \quad (2)$$

Here R_K is the ‘boundary’ resistance per inverse volume of the sinter-helium composite, ρ_M is the thermal resistivity of the mixture within the pores of the sinter, and l is the length of sinter. The bulk thermal conductivity of the ^3He - ^4He mixture has contributions from both phonons and ^3He quasiparticles. The phonon contribution is significant in the bulk for most of our temperature range due to their very long mean free paths. However, within the pores of the sinter, mean free paths become limited by the pore size. Consequently, the phonon contribution to the conductivity within the pores of the sinter is negligible. The mean free path for quasiparticles within the sinter also becomes pore size limited for temperatures below 100mK. We model the thermal resistivity of the mixture within the pores of the sinter by the equation

$$\rho_M = \frac{\gamma}{(1-f)K_{qp}} \frac{\lambda_b}{\lambda} \quad (3)$$

where λ_b ($\approx 5 \times 10^{-10}/T^2\text{m}$) is the quasiparticle mean free path in the bulk mixture, K_{qp} is the quasiparticle conductivity in the bulk (we use the value $K_{qp} = 3 \times 10^{-4}/T \text{WK}^{-1}\text{m}^{-1}$), f is the packing fraction, and γ is a factor which takes into account the tortuosity and possible non-communication of the pores. The quasiparticle mean free path within the sinter pores is obtained by $1/\lambda = 1/\lambda_b + 1/a$, where a is the pore size.

The solid curves shown in the figure are obtained using the above analysis with small corrections at high temperatures to take into account the three dimensional geometry and the small contribution due to the thermal resistivity of the sinter. Since the sinters have a broad distribution of pore sizes, the effective quasiparticle mean free path is calculated using a Gaussian distribution of pore sizes centered on a_0 with a spread of $1.5a_0$. The distribution is weighted by the square of the pore size (larger channels contribute

more to the conductivity). For the C8 Silbest powder we use a mean pore size $a_0=800\text{\AA}$, and for the coarser DC10 powder, $a_0=15000\text{\AA}$. For both types of sinter we use the tortuosity factor $\gamma = 3.1$. The value of the 'boundary' resistance can be obtained directly from the low temperature T^{-3} behaviour, and is found to be $R_K = 5.6 \times 10^{-9}T^{-3}\text{Km}^3\text{W}^{-1}$ for the 800\AA powder and $R_K = 9.8 \times 10^{-9}T^{-3}\text{Km}^3\text{W}^{-1}$ for the 15000\AA powder.

4. CONCLUSIONS

We have found clear evidence for a length scale controlling the thermal transport between silver sinters and a saturated dilute ^3He - ^4He solution. This arises due to the effects of the thermal resistivity of the mixture within the pores of the sinter. At low temperatures, in the size limited quasiparticle mean free path regime, a 'boundary' resistance varying as T^{-3} will give rise to a total thermal resistance varying as T^{-2} for sinters which are thicker than the length scale, Λ . For the 800\AA powder, $\Lambda \sim 1\text{mm}$ at 8mK . We have also found that the 'boundary' resistance R_K (per inverse volume) is rather insensitive to the sinter particle size and sinter surface area (R_K for the 15000\AA powder is only 75% larger than that for the 800\AA powder). Hence the notion of the resistance being a true boundary resistance must be questioned.

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