Exponential Temperature Dependence of the Thermal Boundary Conductance between Sintered Silver and ^{3}He-B in the Region of Low Normal Fluid Density

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We report the first direct measurements of the thermal boundary conductance between superfluid ^{3}He-B and sintered silver in the temperature region well below T_c. The conductance is highly temperature dependent, being dominated by an $\exp(-\Delta/kT)$ dependence in the region $T < 0.3T_c$. Measurements made at the three pressures 0, 4, and 12 bars also demonstrate the variation of the conductance with the energy gap, Δ.

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It has been suspected for some time that the superfluidity of liquid ^{3}He at low temperatures must play a role in the thermal exchange between the ^{3}He and a solid boundary. Whatever mechanism is envisaged for the thermal transport, at some sufficiently low temperature the low normal fluid density must become a limiting factor in the process and one would expect to see a term of the form $\exp(-\Delta/kT)$ reflected in the boundary conductance. A hint of this behavior has been provided by the pressure dependence of the lowest temperatures reached by liquid ^{3}He in a refrigerator where the liquid is observed to cool to roughly the same value of T/T_c independently of the pressure.[1-3]

In this paper we report measurements of the thermal boundary conductance, or, more precisely, of the heat load which can be sustained by liquid ^{3}He-B in contact with a cold refrigerant, as a function of the ^{3}He temperature for $T/T_c < 0.3$. These measurements directly demonstrate that the heat flow to the refrigerant from the helium does indeed reflect this $\exp(-\Delta/kT)$ behavior.

The experiment is carried out in a double cooling cell similar to that described in Ref. 2. The inner cell, $19\times 19\times 50$ mm^3, contains 4.1 cm^3 of liquid ^{3}He in which are immersed twelve 1-mm-thick copper plates each with 0.5 mm of sintered nominally 700-Å silver powder on one face. The powder was presintered in H_2 at 50 °C for 1 h and after pressing was finally sintered for 12 min at a nominal desiccator temperature of 200 °C in H_2. The total weight of powder used was 28 g. This sintering recipe yields an area of 0.8 m^2/g giving approximately 22 m^2 of sinter area in contact with the refrigerant. The cell also contains a Pt NMR thermometer consisting of 2000 insulated 0.025-mm-diam Pt wires fused to a 1-mm-diam silver wire. The wire is spot-welded to a perforated silver foil which is subsequently sintered into a 0.5-mm plate of silver powder (area 2 m^2) which sits beside the copper plates. The "experimental" volume of $10\times 10\times 10$ mm^3 is made by cutting a 10×10-mm^2 square out of seven of the twelve plates. This volume is furnished with a number of vibrating-wire resonators and two heaters as shown in Fig. 1. The resonators are $\sim$8-mm-diam semicircles of wire anchored to the epoxy-soaked paper walls of the inner cell. The wires used in these experiments were (i) 0.124-mm-diam Ta and (ii) $\sim$0.0135-mm-diam NbTi (a single filament of a filamentary superconducting wire) both for use at low temperatures and (iii) a 0.25-mm-diam Ta wire for use at high temperatures to allow the detection of T_c when the damping of the thinner wires by the ^{3}He becomes inconveniently high. The resonators are driven by a Hewlett-Packard model 3325A Synthesizer, and the response voltage analyzed by an EG&G/Brookdeal model 5206 programmable lock-in amplifier. The 0.124-mm-diam resonator is arranged to be part of a bridge circuit in which the response appears as an out-of-balance signal which is amplified by a SQUID before being fed to the lock-in.

The heater used in the experiment is designed to be highly localized (for future possible use in ballistic quasiparticle experiments). The heater element is a 1- to 2-mm length of 0.05-mm-diam bare copper wire

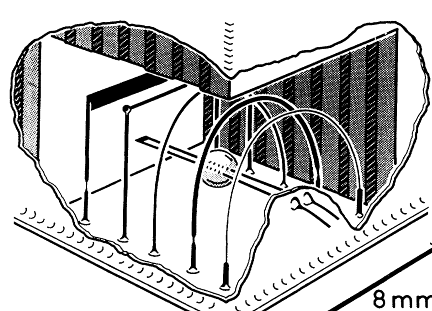

FIG. 1. View of the experiment through a cutout in the epoxy-paper wall of the inner cell. The experimental space is a $10\times 10\times 10$-mm^3 volume cut from the copper plus silver sinter plates. There are three simple wire resonators, the nearest 13.5-μm-diam NbTi, the next 0.25-mm-diam Ta (with two flattened sections to reduce the stiffness), and last 0.124-mm-diam Ta. The heater is sited at the ends of the NbTi leads lying along the axis of the resonators, and is supported by an epoxy bead.

flattened and spot-welded to two NbTi leads held together by a bead of epoxy which also act as the mechanical supports. Since thermal contact to the ^{3}He is made only through the rather limited Cu-^{3}He interface the heater is expected to run rather hot, of the order of tens of millidegrees Kelvin for heating levels in the picowatt range.

The temperature of the ^{3}He can be inferred in two ways. The temperature of the Pt NMR thermometer can be measured directly, but at the lower temperatures the thermometer time constant becomes many hours. In any case there are also problems with the accurate calibration of such a thermometer since the lowest fixed point we can use is T_c for ^{3}He at $P=0$ which is almost a factor of 10 higher than the lowest temperature we can reach. Measurement with the IT PLM-3 electronics also has a number of problems associated with the way the background subtraction is carried out, which means that the absolute value of our Pt temperature scale is not very precise.

Undoubtedly the best available thermometric quantity is the width, Δf_2, of the mechanical resonance of a wire resonator. This quantity probes the quasiparticle gas directly and the response time is limited only by the Q of the resonator. Our previous experiments have shown that below T/T_c of ~ 0.3 the frequency width is linear in $\exp(-\Delta/kT)$ when compared with a Pt NMR thermometer. This very rapid dependence on temperature makes this method of temperature measurement very attractive. Unfortunately the uncertainties in the NMR temperature scale are large enough that we cannot rule out completely the possibility that Δf_2 varies as, say, $T^{1/2}\exp(-\Delta/kT)$ since the $T^{1/2}$ term dependence is too small to be resolved (the addition of a prefactor of $T^{1/2}$ being indistinguishable from changes in the gap-enhancement factor and other constants; see Guénault *et al.*[4]).

The measurements are made in the following way. The cell is demagnetized to the requisite final field and a series of frequency widths, Δf_2, of the 0.124-mm Ta resonator and of the 13.5-μm NbTi resonator are recorded at intervals for increasing levels of heater power, $\dot{Q}$. The values of Δf_2 can be converted into temperature and the procedure yields a series of measurements of the ^{3}He temperature as a function of power. (During this process the thermal time constant of the system can be measured as a function of temperature by the observation of the change in height of the resonance as the heating level is stepped.) The method gives the integrated boundary conductance from the temperature of the refrigerant to the temperature of the ^{3}He. We may assume that the conductance varies so rapidly with temperature that, provided that the temperature of the copper is considerably lower than that of the ^{3}He, it will have no influence on the measured $\dot{Q}$, i.e., the integrated conductance is a function of the helium temperature only. In consequence at the end of a series of measurements the power is turned off and the frequency width again measured as a check that the temperature of the copper has not become significantly higher during the period of heating. Since the quasiparticle mean free paths in the ^{3}He are long throughout the temperature range, heat flow in the liquid is in the radiation limit and we need make no correction for the conductance of the ^{3}He.

relatively small quantity of refrigerant immersed directly in the liquid ^{3}He, means that the highest heating level which can be sustained by the ^{3}He without overwhelming the cooling capacity of the refrigerant is fairly modest. However, the system will tolerate a few nanowatts for short periods so long as the field on the nuclei is fairly high, say 25 mT. At the lower fields used, 7 mT, this level of heating cannot be sustained for more than a few hours without the rapid warming of the refrigerant.

The form in which the raw data appear is shown in Fig. 2 for zero pressure and a field of 25 mT. In the figure the logarithm of heater power is plotted against logarithm of frequency width for the two narrow resonators. We have made measurements at 7 mT but we find no field dependence in the result, data taken at 7 mT falling within 5% of the data in the figure, and all measurements reported here were taken at 25 mT.

The behavior of the 0.124-mm-diam Ta wire resonator is well enough known[4] that we can calculate the T_c/T scale from Δf_2, also shown in the figure. The temperature scale appropriate to the filamentary resonator cannot be calculated *a priori* as the diameter of the filament (the only free parameter) is not well

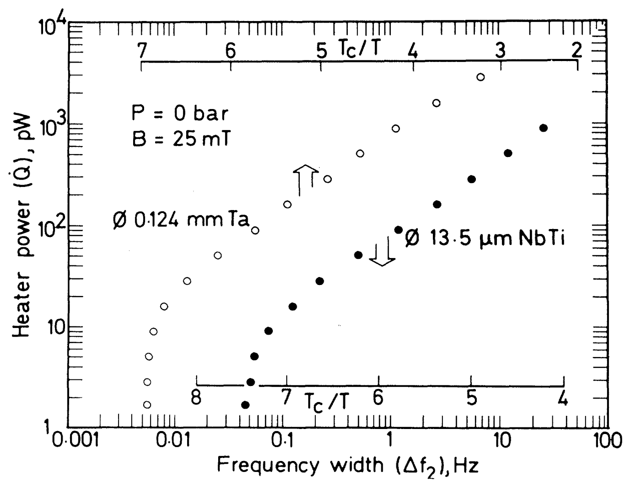

FIG. 2. Raw data taken at 0 bar and 25 mT for the 0.124-mm-diam Ta and the 13.5-μm NbTi resonators plotted as $\log(\dot{Q})$ vs log(frequency width). The temperature scales derived from the frequency widths are also plotted.

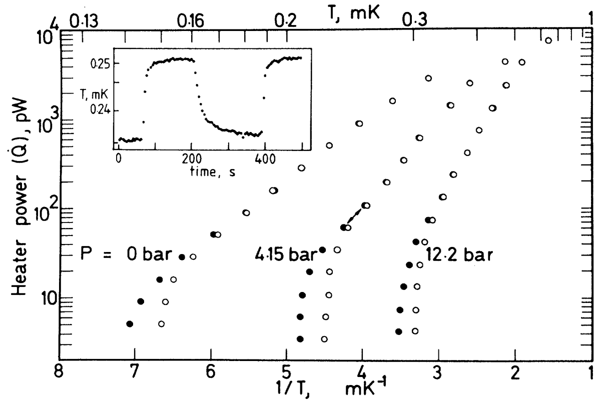

FIG. 3. The data for three pressures plotted as $\log(\dot{Q})$ against inverse temperature; filled points refer to the 13.5-μm NbTi wire, open points to the 0.124-mm Ta wire. Inset: A typical response of the helium temperature as a function of time taken on the 13.5-μm resonator as the heater power is stepped between the two arrowed points at 4.15 bars.

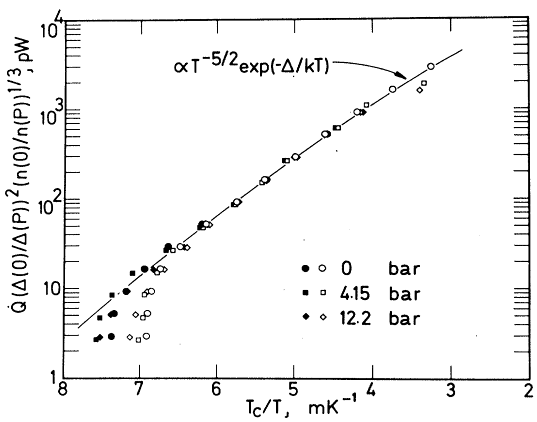

FIG. 4. The data at the three pressures reduced to a common curve. The heater power $\dot{Q}$ is multiplied by a factor $[\Delta(0)/\Delta(P)]^2[n(0)/n(P)]^{1/3}$ and the result plotted against T_c/T. The continuous line represents a temperature dependence of $T^{-5/2}\exp(-\Delta/kT)$.

characterized. We thus "calibrate" the diameter of the filament against the temperature scale of the Ta wire. Since Δf_2 is proportional to $\exp(-\Delta/kT)$ at the lower temperatures, the T_c/T scales are almost linear in the figure except for a slight contraction towards T_c.

The data in the figure fall on straight lines with slope near to unity, indicating that since Δf_2 varies as $\exp(-\Delta/kT)$ the integrated thermal conductance also shows the same approximate temperature dependence. The droop at low temperatures arises from a combination of the vacuum width of the wire, interactions with the texture, and the residual heat leak into the ^{3}He. The data also have a tendency to fall below the line at very high heat fluxes. Here the resonator response also becomes rather noisy, which we tentatively interpret as an instability setting in, possibly in the region of high heat flux near the heater.

We have made similar measurements at the three pressures 0, 4.15, and 12.2 bars (i.e., at approximately equal intervals of Δ). The results are shown in Fig. 3, where the Δf_2 values have been used to place all the data on a common temperature scale. Since the slope should be approximately Δ/k the gap dependence is clearly seen.

The inset in the figure is a representative thermal response of the liquid as the heating level is alternated by one increment. The thermal response times at all temperatures and all three pressures lie in the 10- to 25-sec region. If we calculate a time constant from the known heat capacity of the ^{3}He at the temperature indicated by the resonator and the measured boundary resistance (the temperature derivative of the quantity plotted in Fig. 3), we would expect a time constant a factor of 10 shorter. However, it is quite probable that a bubble of hot normal ^{3}He surrounds the heater. This might represent a very large heat capacity compared with that of the bulk superfluid. Nevertheless, the thermal relaxation is very fast compared with the usual thermometer time constants at the lowest temperatures. For example, after measuring the highest temperature point at 12.2 bars in Fig. 3, we began a sweep of the filamentary resonator at the same time as the heating was switched off. There followed a minute or so of chaotic behavior, but by the time the frequency sweep had reached the resonant frequency after 300 sec the line recorded was 0.04 Hz wide, as low as we ever see with this resonator.

The data can be reduced to a single T/T_c dependence as shown in Fig. 4 in which data for all three pressures are plotted against T_c/T. The values of $\dot{Q}$ are corrected by a reduction factor $[\Delta(0)/\Delta(P)]^2[n(0)/n(P)]^{1/3}$ where n is the number density of the ^{3}He. (The number density is taken from Wheatley[5] and the values of Δ taken as proportional to the critical temperatures of the data of Alvesalo *et al.*[6]) The precise form of reduction factor should not be taken too seriously. The range of T_c/T is not very large and convincing curves can also be produced with a factor $[\Delta(0)/\Delta(P)]^2[n(0)/n(P)]^{2/3}$. In fact, we might expect the pressure dependence to contain $n(P)^{2/3}$, the density of states squared, if quasiparticle scattering is involved. The continuous line through the data represents a temperature dependence of the form $T^n\exp(-\Delta/kT)$, with Δ taken as $1.94kT_c$ and the value of $n\,(=-\frac{5}{2})$ chosen to fit the data. This is not a unique parametrization, however, and fair agreement may also be obtained with more positive values of n, compensated by smaller values of Δ.

The magnitude of the conductance is surprisingly high. Representative values of the conductance taken from Rutherford, Harrison, and Stott[7] for the normal state and extrapolated to lower temperatures yield values of $\dot{Q}$, the integrated conductance, which are of similar magnitude to the 0-bar superfluid data at 0.3 mK. There may be a difficulty here in comparing like with like. If we assume with Rutherford, Harrison, and Stott[7] and Lambert[8] that the contact to the solid is made via low-frequency phonon modes in the "soft" sinter-^{3}He composite, then the absolute microscopic area between sinter and liquid may not be very relevant. More appropriate quantities for comparison might be either the total bulk sinter volume or the interfacial area between bulk sinter and bulk liquid, which in our case has been deliberately made as large as practicable. A high apparent conductance might also be measured if a fraction of the heater power were lost through phonon conduction via the superconducting leads into the outer cell. We have verified that this is not the case by calibrating the heater at the 100- to 1000-pW level against the copper heat capacity at higher temperatures.

In conclusion, we can quote the integrated interfacial boundary conductance for the whole cell as

$$\dot{Q} = 2.46\times 10^{-3} T_c^{9/2} \exp(-\Delta/kT)/(V^{1/3}T^{5/2}) \text{ W},$$

where V is the molar volume in cubic meters. The precise functional form should be read as a means of parametrizing the data rather than indicating any firm dependences. For purposes of comparison the relevant parameters of the cell are microscopic surface area of sinter, 22 m^2; mass of silver sinter, 28 g; and bulk sinter to bulk ^{3}He interfacial area, 0.011 m^2.

We hesitate to draw any firm conclusions on the precise mechanism by which the heat is transferred, especially since the situation in the normal fluid is far from clear. Certainly the best candidate for the conduction mechanism is the inelastic scattering of quasiparticles at the boundaries exciting low-lying phonon modes in the sinter. It is, however, of interest to note that when the heating level is stepped we observe that the quasiparticle number density can change by a factor of 2 in a few seconds. This is actually faster than the calculated quasiparticle-quasiparticle scattering time in the bulk liquid at the lowest temperatures, which seems to indicate that the walls must play a role in bringing quasiparticles together for recombination at a rate faster than that expected in the bulk liquid. On the other hand, one would expect any contribution to the conductance from a recombination mechanism to reflect the two-particle nature and yield a rate varying as the square of the gap Boltzmann factor, which we do not see.

It is possible that the superfluid regime may turn out to be a simpler subject for the study of heat transfer than the normal regime. It would certainly be interesting to repeat the experiment with silver of a different particle size to look for evidence of the influence of low-frequency modes in the sinter.

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