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Anomalous thermal boundary resistance of superfluid ^{3}He-B

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The observation of a pressure dependence to the limiting temperatures attained in a liquid-^{3}He sample implies an additional thermal boundary resistance for superfluid ^{3}He-B. The measured time constants for thermal relaxation provide confirmation of this boundary resistance, which exhibits an exponential temperature dependence.

It has been a common observation[1-3] that the lowest temperature achieved in ^{3}He liquid during the course of a nuclear demagnetization experiment is strongly pressure dependent, providing that temperatures below ~ 0.4 mK at saturated vapor pressure can be obtained. At the lowest temperatures attained, the time constants for equilibration can increase rapidly.[3,4] The two effects are not unrelated. In this Rapid Communication, I present data which suggest that these effects are due to a novel thermal boundary resistance which displays an exponential temperature dependence. Mechanisms which may contribute to this boundary resistance include Andreev scattering,[5,6] size effects on the thermal conductivity of the superfluid within the sinter,[1] and effects related to magnetic ordering in the first few layers of ^{3}He on the heat-exchanger surface.[7]

The data presented in this Rapid Communication were taken in the course of eight separate demagnetizations at different pressures of the liquid-^{3}He sample ranging from 0 bars (saturated vapor pressure) to 29.15 bars. The demagnetizations were performed under virtually identical starting conditions, and followed a standardized routine.[8] Unfortunately, the data were not taken specifically with a view to exposing the temperature dependence of the boundary resistance, and consequently the response times at intermediate temperatures during the demagnetization were not well resolved. The temperatures and time constants were measured by observing the response of a standard lanthanum-diluted cerium magnesium nitrate (LCMN) paramagnetic salt thermometer calibrated against the melting curve of ^{3}He.[9] The thermal response of the liquid ^{3}He could also be observed with a torsional oscillator.[9] It is appropriate to add that the thermometry in this temperature range is based on an extrapolation from 1 mK, and may therefore be subject to systematic errors. The thermometer was immersed inside the liquid-^{3}He sample of volume 7 ml. Thermal contact between the liquid helium and the nuclear stage was provided by a heat exchanger consisting of a 30-m^2 area of bronze flakes sintered in the interstices of a square array of 2.52 mm^2 copper posts spaced 3.18 mm between centers, providing a "bulk" interface area of 500 mm^2 between the liquid and the heat exchanger.[8]

In Fig. 1(a), the lowest temperatures achieved in the course of demagnetization to a residual field of 0.029 T are shown as a function of pressure. The pressure dependence of the minimum temperature closely mimics that of the pressure dependence of the superfluid transition temperatures, as can be seen in Fig. 1(b), where the reduced temperature T/T_c is plotted against the pressure. It is evident that the bulk of the pressure dependence is removed by this normalization. Similar conclusions can be drawn for data from other laboratories.[1-3]

From our measurements of the reversibility of the demagnetizations,[8] it is likely that the limiting temperature of the nuclear stage is on the order of 0.2 mK. Since the ^{3}He represents a negligible heat load on the nuclear stage, it is reasonable to assume that the final temperature of the nuclear stage is unaffected by the pressure of the liquid ^{3}He. The overall heat leak to the nuclear stage was measured to be 0.7 nW independent of the pressure. Using standard estimates of the thermal resistances, it is possible to explain the difference in temperature between the ^{3}He and the nuclear stage by assuming that the entire heat leak enters through the liquid and in addition, that the "ordinary" Kapitza resistance's coefficient increases by a factor of 6 at the elevated pressure. Such a large increase in the thermal

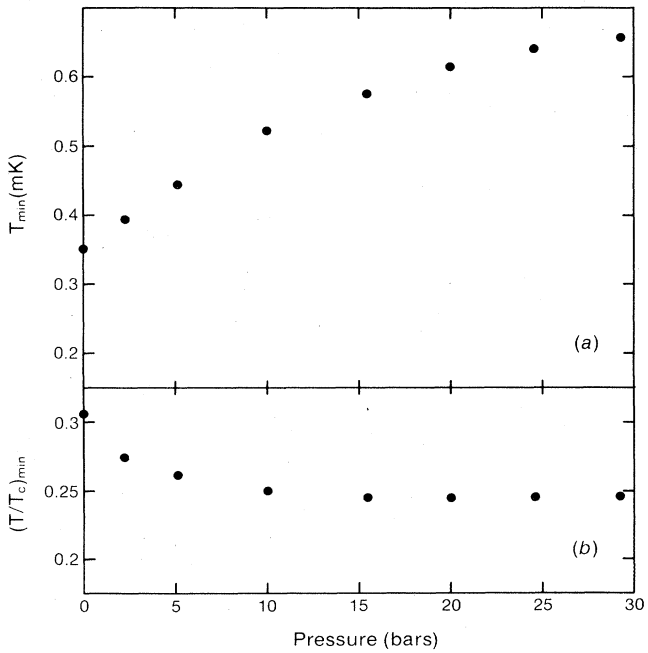

FIG. 1. (a) The limiting temperature achieved in the liquid-^{3}He sample while following a fixed demagnetization routine. The pressure was varied between 0.0 (nominal) to 29.18 bars. (b) The limiting values of T/T_c, the normalized temperature. The majority of the pressure dependence is removed by this normalization.

offset was not observed in comparisons between the LCMN thermometer and the separate melting-curve thermometer[9] at temperatures above 1 mK. A corresponding increase in the thermal time constants at elevated pressures above 1 mK was also not observed, implying that the increased resistance originates from a property of the ^{3}He at low temperatures rather than from an increased ordinary Kapitza resistance.

In order to determine the magnitude of the additional resistance, the thermal time constants were determined from the thermometer's response, following a demagnetization to a particular magnetic field. The time constant for the thermometer was found to agree well with the response of the torsional oscillator, indicating that the response is characteristic of the liquid's temperature and not governed by a time constant intrinsic to the thermometer. The results for values of $T/T_c > 0.4$ reveal that the time constant τ is ~ 1000 seconds with relatively little pressure dependence. However, as the temperatures were lowered further, the time to equilibrate at the lowest temperature increased dramatically, exceeding 24 hours at the highest pressure. These time constants for all eight pressures are shown in Fig. 2. The value of the time constant at a particular temperature allows the determination of the magnitude of the thermal resistance through the usual formula

$$\tau = RC \ , \tag{1}$$

where R is the total thermal resistance and C is the heat capacity of the liquid helium, which is calculated from the theoretical expression valid at low temperatures:[10]

$$C(T/T_c) = (2\pi)^{1/2}(3/\pi^2)(1.76)^{5/2}\gamma R T_c (7/V_m) \times (T_c/T)^{3/2}\exp(-\Delta_0/kT) \ . \tag{2}$$

Here γ is the coefficient for the specific heat in the normal liquid,[11] R is the gas constant, V_m is the molar volume, Δ_0 is the zero-temperature gap which is assumed to be $1.76kT_c$, and the factor 7 enters in as the volume of the cell in ml. The thermal resistances calculated from this procedure are shown in Fig. 3, where the symbols used correspond to those used in Fig. 2.

A check on the magnitude of the thermal resistances can be determined by assuming that the temperature gradient imposed by the existence of the additional boundary resistance is given by $\Delta T = (T_{\min} - 0.25\ \text{mK})$, where I assume that the temperature of the copper heat exchanger is 0.25 mK. From the calculated thermal resistance and the measured minimum temperatures, a pressure-independent heat leak to the liquid on the order of 10 pW may be inferred. This heat leak is approximately 1.5% of the total heat leak to the nuclear stage and, though small in magnitude, is larger than that calculated for the heat input through the fill line, wiring, and other possible heat sources.

In order to try to estimate the dominant temperature dependence of this resistance, the inferred thermal resistances were plotted as a function of the inverse reduced temperature in Fig. 3. From this figure it can be seen that the thermal resistance follows the relation $R = R_0 \times \exp(\alpha\Delta_0 kT)$, where $R_0 = 8.4\times10^3$ (K/W) and $\alpha = 1.25 \pm 0.5$. The error in the exponent α arises from uncertainties in the heat capacity of the ^{3}He and the temperature scale.

An exponential dependence to the thermal boundary

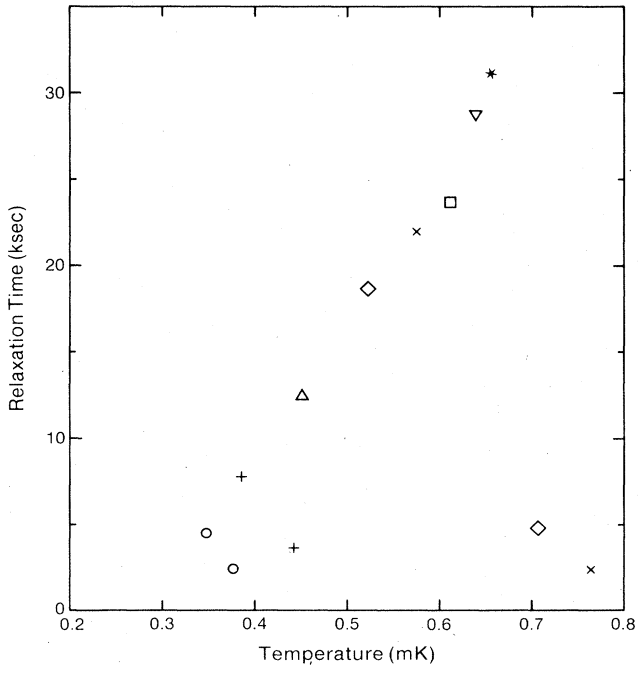

FIG. 2. The measured time constants for equilibration following a demagnetization to a low field at several pressures. $p = 0$ bars (○), 2.18 bars (+), 5.1 bars (△), 10.0 bars (◇), 15.4 bars (×), 19.96 bars (□), 24.47 bars (▽), and 29.15 bars (*). The pressure dependence is evident and is partially due to the increased heat capacity of the liquid (see text).

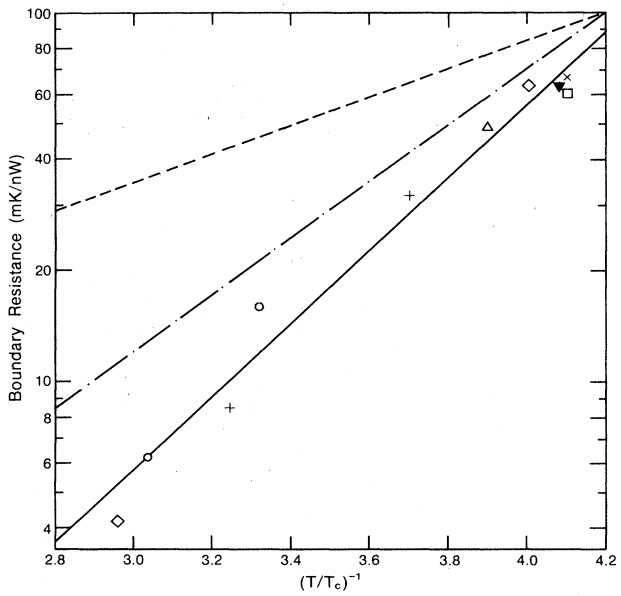

FIG. 3. The thermal resistance as a function of the inverse reduced temperature. The straight line is a fit through the data exhibiting a temperature dependence of $\exp(1.25\Delta_0/kT)$. The other lines are included to allow a comparison to the possible variation of the boundary resistance with $\exp(0.5\Delta_0/kT)$ (− − −) and $\exp(\Delta_0/kT)$ (− · − ·).

resistance can have several origins. The simplest model was outlined by Varoquaux,[1] in which the thermal conductivity of the ^{3}He in sintered material is limited by the pore size. If the thermal gradient along the pore is set equal to the temperature gradient due to the usual Kapitza resistance, then a length L can be defined by

$$L=(\kappa d/4h_K)^{1/2}=[(\tfrac{1}{3})CV_Fd^2/4h_K]^{1/2}\,, \tag{3}$$

where C is the heat capacity per unit volume, κ the thermal conductivity of the ^{3}He, V_F the Fermi velocity, d the pore diameter, and h_K the Kapitza conductance . Using Eq. (2) for the heat capacity, L decreases approximately as $\exp(-\Delta_0/2kT)$. If the thickness of the sinter is greater than this length, the thermal resistance would be governed by the finite conductivity of the ^{3}He in the pore and would increase as $\exp(\Delta_0/2kT)$. However, under the assumption that $d=0.5$ μm and using the observed limiting values of T/T_c, the crossover lengths at the minimum temperatures are estimated to be between 10 and 6 mm, approximately an order of magnitude greater than the actual thickness of the sinter. The expected $\exp(\Delta_0/2kT)$ dependence to the thermal resistance is also not observed in this experiment (see Fig. 3).

Recent theoretical work on the scattering of excitations from spatial variations of the energy gap Δ_0 (Refs. 12 and 13) has shown that this mechanism can play a dominant role in the transfer of momentum at the bulk ^{3}He-solid interface.[6,14] Gradients in the magnitude of the energy gap lead to a reflection coefficient that approaches unity for quasiparticles having energies close to the gap energy. This reflection process (Andreev scattering) thus impedes energy exchange at the surface. Greaves and Leggett[14] calculate that an additional "pseudo-Kapitza-resistance" should dominate at temperatures below $\sim 0.15T/T_c$ in the A phase. Since the reflection coefficient depends on the gradient of the gap, which in the B phase is approximately two orders of magnitude larger than in the A phase, the corresponding reflection coefficient should be enhanced over that of the A phase. The thermal resistance should display a dependence[14]

$$R(T/T_c)\propto e^{\Delta_0/kT} \tag{4}$$

similar to that calculated for the A phase and consistent with the results in Fig. 3. The temperature dependence of this resistance is a consequence of the energy dependence of the reflection coefficient together with the exponential temperature dependence of the number density of the excitations in ^{3}He.

As a check, the results for the exponential resistance were used to model the performance of the Bradley *et al.* double-cell demagnetization cryostat.[3] Taking into account the larger bulk ^{3}He contact area for their cell, the calculated time constants for 0 bars at 0.12 mK would be ≈ 6000 sec, (comparable to those measured in the double-cell experiment), and, in order to produce a thermal gradient of 0.1 mK, the heat leak to the liquid would have to be ≈ 10 fW.

In summary, a thermal boundary resistance which dominates the heat-transfer process at low values of T/T_c in the superfluid B phase has been identified. Preliminary investigations of this boundary resistance are consistent with the model of an exponentially increasing thermal resistance, $R\propto\exp(\Delta/kT)$. The data and identification can be significantly improved by specifically designing a heat-exchange cell to measure the thermal resistance at low temperatures directly, avoiding possible errors due to assumptions of the temperature dependence of the heat capacity of the ^{3}He.

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