Novel Magnetic Field Dependence of the Coupling of Excitations between Two Fermion Fluids

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We have observed a new magnetic field dependence to the thermal boundary resistance between liquid ^{3}He and finely powdered silver particles. At a temperature of 1 mK we find the thermal boundary resistance to increase by nearly an order of magnitude as the magnetic field is raised from 0 to 200 mT. This behavior cannot be explained by conventional acoustic models of the heat conduction. By contrast, however, we observe no field dependence from 0.2 to 9.4 T, in strong contradiction to the behavior expected based on the recent conduction model of Perry *et al.*

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The processes by which heat is transported across the boundary between a metal and liquid ^{3}He at very low temperatures are still not well understood, despite the role this system plays as a model for the thermal transport between two degenerate Fermi fluids. Unlike the phonon heat transport between ^{4}He and metals in which the thermal resistance varies as T^{-3}, many measurements have shown that for pure ^{3}He the boundary resistance varies as T^{-1} at temperatures below about 10 mK.[1] Recently Perry *et al.*[2] showed that between liquid ^{3}He and platinum powder the boundary conduction is enhanced by the application of magnetic fields from 0.2 to 1 T, in contrast to phonon models which predict no field dependence. These authors have suggested a coupling mechanism to explain their results which is based on the direct interaction between conduction electrons in the metal and the nuclei of ^{3}He atoms adsorbed at the metal-liquid interface. Our present measurements show that this mechanism is not important at the silver-^{3}He interface, probably because of a substantial amount of oxygen adsorbed on the silver surfaces. At the same time, however, we observe a very strong field dependence at much lower fields, which we feel may result directly from the presence of this adsorbed oxygen.

We have measured the thermal boundary resistance between liquid ^{3}He and a silver-powder heat exchanger consisting of 36 g of Ulvac[3] silver powder type II. The powder was compressed under 200 bars pressure to a packing fraction of 45% around forty 1-mm-diam high-conductivity silver posts as shown in the inset to Fig. 1. These posts were welded to a 0.63-cm-thick silver base plate, and twenty 1-mm-diam holes were drilled into the heat exchanger to improve thermal contact.[4] Adsorption isotherms indicated an average surface area of 2.0 m^2/g, implying an average particle size of 3000 Å. Chemical analysis has shown the silver powder to contain less than 50 ppm impurity levels of virtually everything except for molybdenum (0.2% by weight) and oxygen (0.15% by weight). Our heat exchanger was not "sintered," although it was heated to 50 °C for several hours during the process of cell assembly. For similar powder this treatment resulted in an electrical resistivity in the powder of 12 $\mu\Omega$ cm. Boundary-resistance measurements were made at 0, 10, 20, and 30 bar pressures with ^{3}He containing less than 2 ppm ^{4}He impurities.

The lower portion of our sample chamber is shown schematically in Fig. 1. Below the heat exchanger a demountable nylon NMR tail piece was attached which contained a vibrating-wire viscometer to detect the superfluid transition, a fused-silica capacitance thermometer, and a platinum NMR thermometer which operated in a field of 0.385 T. A heater consisting of a 30-cm length of Pt-W wire was positioned as close as possible to the heat exchanger. All temperatures used in this work were measured with the capacitance thermometer, which was calibrated against the NMR thermometer at 0.385 T or against the temperature of the

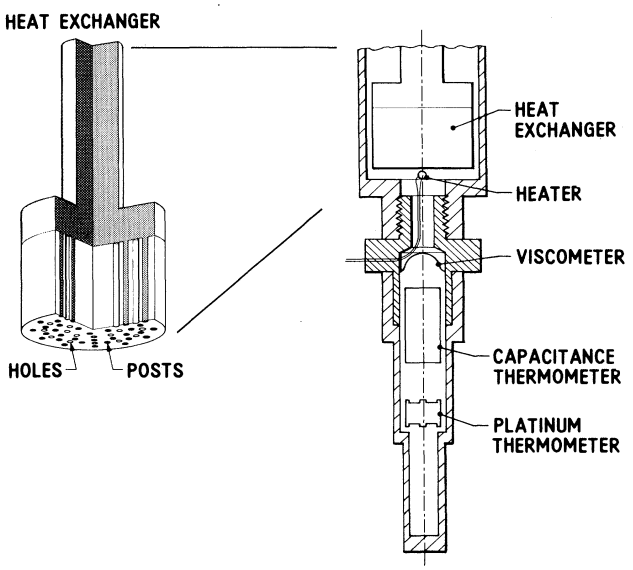

FIG. 1. Schematic diagram of the lower portion of our experimental cell. The insert shows a cutaway drawing of the heat exchanger.

nuclear bundle in zero field. This latter calibration technique was made possible by the low (0.7 nW) heat leak into the nuclear stage in zero field, and the two techniques agreed to within our calibration accuracy of about 7 μK. The temperature scales were adjusted by a multiplicative factor at each pressure so that our measured values of T_c agreed with the Helsinki phase diagram[5] adjusted in a similar manner so that $T_c(P_{\text{melt}}) = 2.75$ mK. The heat exchanger was attached to a copper nuclear stage consisting of 60 moles of 400-μm-diam copper wire. In an rms magnetic field of 6 T, precooled to 8 mK, we achieve a heat capacity in our nuclear stage in excess of 85 J/K.

The boundary resistance was measured by applying a constant, known amount of power to the Pt-W wire until thermal equilibrium had been achieved throughout the cell. The power was then removed, and a new equilibrium temperature was obtained. The amount of power was adjusted so that $T_{\text{hot}} - T_{\text{cold}}$ was typically $0.07 T_{\text{ave}}$. We then determined the product RT using the relationship that $RT = (T_{\text{hot}}^2 - T_{\text{cold}}^2)/2\dot{Q}$. This equation is valid even for large $\Delta T/T$ provided RT is temperature independent. Presenting our results in this manner facilitated our correction for the thermal resistance associated with the metallic heat path to the nuclear bundle described below.

The above procedure actually measures the sum of all thermal resistances between the ^{3}He and the nuclear bundle. Most notably, these include the resistance of the silver components which connected the heat exchanger to the bundle, and the thermal resistance of the ^{3}He itself. In order to measure the metallic contribution, we included a second heater on the silver rod connecting the heat exchanger to the nuclear bundle where it entered the cell. By applying the above procedure using this heater, we determined that the product RT from that point to the bundle was 3.3 ± 0.4 K^2/W, independent of temperature. On the basis of measurements of the electrical resistivity of the other materials in the heat path and their known geometry, we have calculated the additional metallic contribution to be 1.7 ± 0.5 K^2/W, and have therefore subtracted 5 K^2/W from all the results we present below. The ^{3}He resistance is more complex, consisting of a bulk term for which RT scales as T^2, and a pore term for the ^{3}He inside the pores of the heat exchanger for which RT is constant in the limit of a constant quasiparticle mean free path. We measured the bulk term at 30 bars at 15 and 20 mK where the boundary resistance is negligible and all the heat enters the metal near the bottom of the heat exchanger. We then scaled the measured resistance to other temperatures and pressures using the known thermal properties of liquid ^{3}He.[6] The bulk contribution required a correction to RT in the normal liquid of 0.252, 0.190, 0.136, and 0.086 times T^2 K^2/W at 30, 20, 10, and 0 bar pressures. We modeled the pore resistance assuming a 3000-Å mean free path, and used a computer to solve the linearized heat flow equations. The results in the normal phase are believed accurate to within ± 1 K^2/W below 4 mK, probably quite a bit better for low sample pressures and temperatures. We have not attempted to account for the ^{3}He thermal resistance below T_c.

The boundary resistance data at saturated vapor pressure (SVP) in zero and 0.385 T magnetic fields are shown in Fig. 2. The solid curve at the bottom of the figure represents the ^{3}He related thermal resistance (times temperature) which has been subtracted from the data. Even at 4 mK the high-field resistance is nearly twice that in zero field, and at 1 mK it is nearly ten times the zero-field resistance. Such behavior has to our knowledge never before been observed, yet it was seen consistently at all pressures. Notice that $R_b T$ is almost constant at 0.385 T, but only for temperatures above about 3 mK. This behavior was also seen at higher pressures. As the pressure was raised, we began to see a drop in the total thermal resistance just below the superfluid transition. In all cases, this drop was within 30% of our estimate of the ^{3}He contribution to the total resistance at that temperature, and we do not find strong evidence to suggest that the boundary resistance is affected by superfluidity in the liquid. The near equality of the drop in total resistance at T_c and our estimate of the ^{3}He contribution is probably an indication that our modeling of the liquid thermal resistance is fairly accurate.

Previous values of the ^{3}He-silver boundary resistance[7] were mostly measured in a 28.4 mT magnetic field, and RT was found to be independent of temperature. Curiously, in data we have obtained in the same

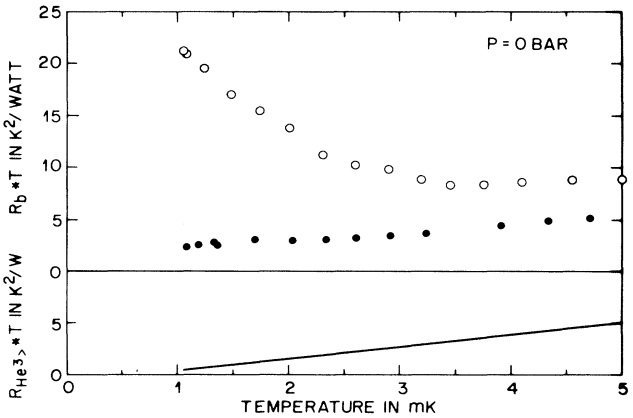

FIG. 2. Temperature dependence of $R_b T$ at SVP in 0.385 T (open circles) and zero (solid circles) magnetic fields. The solid curve at the bottom is our estimate of the thermal resistance of the ^{3}He, which has been subtracted from the data (see text).

field at 10 and 20 bar pressures, we measure the same result, with a magnitude comparable to the previous measurements. In this field there is a fortuitous compensation of temperature dependences.

As the pressure was raised at constant temperature, R_bT was seen to increase, by about a factor of 2 at 3 mK in zero field, and slightly less at 0.385 T. The temperature dependence of R_bT in zero field also increased. At 0.385 T at all pressures R_bT was nearly independent of temperature until it began to rise below 3 mK. This dependence of R_bT on pressure, to our knowledge, has never been reported, and is in the opposite sense to what one would have expected for a conduction mechanism based on phonons. It is also opposite to the sense predicted by more complex acoustic models such as Harrison's composite-medium model.[7]

The transition from the zero-field to the high-field boundary-resistance behavior is shown in Fig. 3 for two sample pressures near 1 mK. We have not corrected these data for the thermal resistance of the ^{3}He, which should be small except perhaps at 29 bars in the pores of the heat exchanger. Both sets show similar behavior, with the resistance doubling from its zero-field value in a field of about 20 mT, and saturating in fields above about 0.2 T. This behavior suggests that two conduction mechanisms are important in low fields, and that one of them is suppressed by the presence of the magnetic field. The characteristic field for this suppression, 20 mT, seems at first somewhat difficult to understand, since at the field at 1.1 mK $\mu H/kT$ is only about 0.01 for ^{3}He nuclei, but is about 10 for electrons. Anderson has pointed out that dipole-dipole interactions would probably broaden the Zeeman levels of any localized electronic moments by several tens of milliteslas, however, and that our characteristic field is probably a measure of the broadening of these levels. From the characteristic field at which the low-field behavior disappears, we can determine that for this model to be correct, the spacing between magnetic impurities must be about 5 Å. The only impurity which our silver particles contained in sufficient numbers to satisfy this constraint was oxygen, which is known to chemisorb to silver in a variety of magnetic forms. Although the average spacing between the oxygen molecules on our surfaces was actually only 3.3 Å, it is unlikely that all the oxygen existed in magnetic forms.

Despite the strong dependence of R_bT on small magnetic fields, we do not see dependence at high fields. In Fig. 4 we present the behavior of R_bT measured at 2.7 mK over the field range from less than 2 mT to 9.4 T at SVP. Except for the initial rise at low fields, the boundary resistance is field independent over the entire range of fields used. We have not corrected these data for magnetoresistive effects; however we can estimate that these effects add no more than 1.1 K^2/W to the measured resistances.[8] The absence of any dependence of R_bT on magnetic field above 0.3 T is in sharp contrast to the behavior seen in the platinum-^{3}He system, and indicates that the mechanism suggested by Perry *et al.*[2] is not important in our heat exchanger. This is probably not surprising considering the oxygen on our silver surfaces, but the fact that we measure a boundary resistance at intermediate fields comparable to that measured by a number of other investigators[1] suggests that the mechanism presented by Petty *et al.* is not necessary to

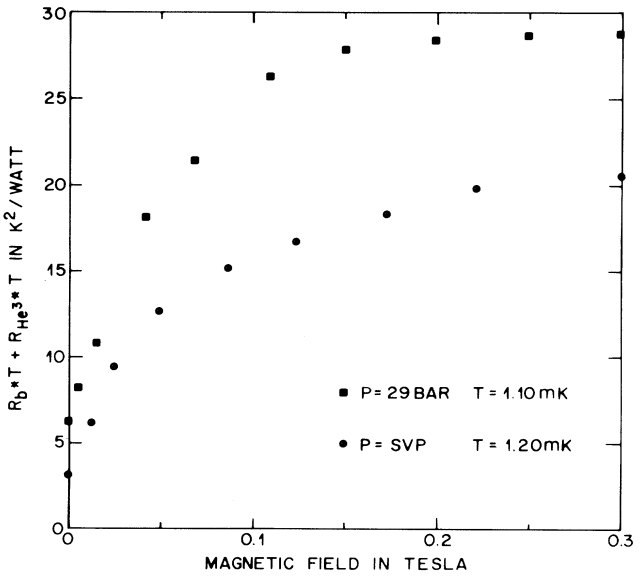

FIG. 3. Magnetic field dependence of R_bT at 29 bars (squares) and SVP (circles) sample pressures near 1 mK from zero to 0.3 T.

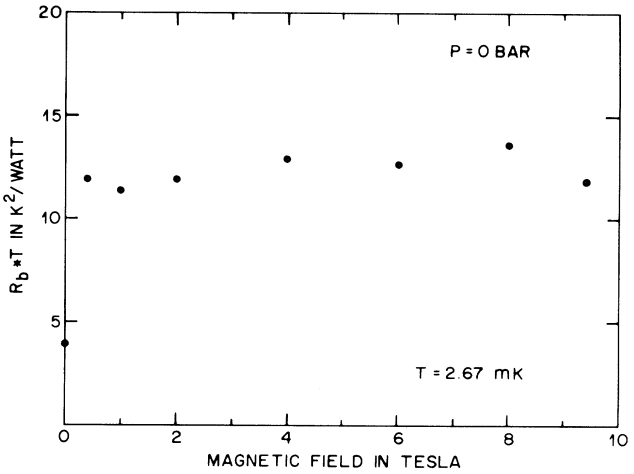

FIG. 4. Magnetic field dependence of R_bT at SVP and 2.67 mK for 2 mT $< H <$ 9.4 T. The absence of field dependence above 0.2 T was unexpected.

explain the very good thermal contact between liquid ^{3}He and silver at temperatures below 10 mK.

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[1]For a review of the data and phonon transport models see J. P. Harrison, J. Low Temp. Phys. **37**, 467 (1979), and T. Nakayama, in *Proceedings of the Fourth International Conference on Phonon Scattering in Condensed Matter,* edited by W. Eisenmenger, K. Lassann, and S. Doettinger (Springer-Verlag, Berlin, 1984).

[2]T. Perry, K. DeConde, J. A. Sauls, and D. L. Stein, Phys. Rev. Lett **48**, 1831 (1982).

[3]Ulvac Vacuum Metallurgical Co., Ltd., Shonan Bldg. 14-10, 1 Chrome-Chuoku, Tokyo, Japan.

[4]This procedure works only with unsintered powders, otherwise smearing of the metal produces low-porosity surfaces.

[5]T. A. Alvesalo, T. Haavasoja, and M. T. Manninen, J. Low Temp. Phys. **45**, 382 (1981).

[6]See D. S. Greywall, Phys. Rev. B **29**, 4933 (1984), or J. C. Wheatley, Rev. Mod. Phys. **47**, 415 (1975). The more recent values show a 17% larger change in conductivity—between SVP and 30 bars sample pressure. We have used the earlier values in our calculation, although the difference does not affect our results significantly.

[7]A general summary of existing data is given by A. R. Rutherford, J. P. Harrison, and M. J. Stott, J. Low Temp. Phys. **55**, 157 (1984).

[8]J. O. Strom-Olsen, Proc. Roy. Soc. London, Ser. A **302**, 83 (1976).