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[8]If one takes the ratio of Γ at two different r_i, it is possible to get the relative size of the matrix elements at these points.

Improved Thermal Contact at Ultralow Temperatures between ^{3}He and Metals Containing Magnetic Impurities

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For Pd containing 30 ppm Fe, and for Au containing 0.2% Gd, we have found a thermal boundary resistance that is approximately proportional to T^{-1} below 20 mK. The improvement in heat transfer is, at 4 mK, a factor of 50 for the Pd sample and a factor of 20 for the Au sample over that expected for phonon conduction in the same samples. The mechanism for thermal transfer is thought to be a direct coupling between the magnetic moments of the impurities and the ^{3}He nuclei.

Each of the two methods that has been used to cool ^{3}He to temperatures in the millikelvin region has important limitations: Compressional or Pomeranchuk cooling produces a mixture of solid and liquid at a pressure that is determined by the details of the compression and which cannot be varied independently, and adiabatic demagnetization of cerium magnesium nitrate (CMN) cannot produce temperatures below its ordering temperature. The interest in the properties of ^{3}He at temperatures of 1 mK and lower provides an incentive for the development of other methods of cooling, and the most obvious alternative is by adiabatic demagnetization of nuclei in a metal. Attainment of lower temperatures than those accessible by demagnetization of CMN, however, would require a substantial reduction in the Kapitza or thermal boundary resistance, R_B, at the metal-^{3}He interface. In the usual case of heat transfer by phonons, $R_B \propto T^{-3}$. For Cu the proportionality constant can be reduced by work hardening[1] or precipitation hardening.[2] For Pt, $R_B \propto T^{-2}$ and increases with the addition of low concentrations of ^{4}He, and it has been suggested that the conduction electrons may be directly coupled to the ^{3}He nuclei.[3] However, the lowest values of R_B in the millikelvin region have been found for the CMN-^{3}He interface for which $R_B \propto T$.[4] In that case it has been shown that the energy transfer can be accounted for by a magnetic dipole coupling between the Ce^{+3} ions and the ^{3}He nuclei.[5] These results suggest that the low values of R_B that would be necessary to make nuclear cooling in a metal an attractive method for cooling ^{3}He to temperatures near 1 mK might be achieved by the introduction of impurities with localized magnetic moments. We have made measurements on several systems to test this possibility. The initial results are encouraging, and are reported here.

TABLE I. Characteristics of the Kapitza-resistance samples.

Sample	Impurities Gd (%)	Cr (ppm)	Mn (ppm)	Fe (ppm)	Co (ppm)	Ni (ppm)	Foil thickness (μm)	Surface area (cm^2)
Cu	•••	<2	3	10	<0.5	•••	50	600
Pd	•••	22	3	32	•••	13	125	254
Au	0.2	<5	<1	1	<3	<3	60	327

The Kapitza-resistance sample was surrounded by 63 g of CMN, ground to pass a 37-μm sieve. The sample (except for the part attached to the thermometer and the heater) was immersed in 0.9 mole of liquid ^{3}He which also penetrated the interstices in the CMN. The whole assembly was precooled to 15 mK with a dilution refrigerator, and demagnetization of the CMN from that temperature and 80 mT produced a final temperature of 3 mK. The measurements of R_B were made as the cell warmed under the influence of the residual heat leak.

The samples were made of thin foils, welded at the top to a 1.5-mm thick, 99.999%-pure annealed Cu wire. This wire in turn was welded to a piece of the same Cu that was used for measuring the temperature of the sample. The temperature of the sample was obtained by employing a superconducting quantum interference device (SQUID) technique to measure the static nuclear susceptibility of the Cu and assuming a Curie law for the nuclear susceptibility. The SQUID thermometer was calibrated against a ^{54}Mn*Ni* nuclear orientation (NO) thermometer, in the temperature range from 10 to 40 mK. In these measurements the shortest time constant observable is τ_1 for the Cu nuclei, given by the Korringa relation $\tau_1 T = 1$ sec K, at fields used in the flux trapping tube. τ_1 is indeed the only time constant observable in all runs except the one in which the Au sample was investigated. In that case the nuclear heat capacity, C_N, of the impurities was large enough to make the time constant $\tau = R_B C_N$ dominant. In addition to these thermometers a SQUID-CMN thermometer and a few sliced carbon thermometers were used to measure the temperature of the ^{3}He liquid in various parts of the cell. A heater was attached to the top of the sample and R_B was determined by measuring the steady-state temperature difference between the sample and ^{3}He for a constant heater power.

Table I gives the impurity contents and dimensions of the three samples for which measured values of R_B are shown in Fig. 1. Measurements on several Cu samples of different thickness were made to investigate the possibility[6] that R_B might be anomalously high for thin foils. However, in agreement with other work,[7] it was found that any such effect is smaller than differences arising from surface treatment, and for clarity we show our results on only one Cu sample. Above 7 mK, $R_B T^3$ is approximately constant for the copper sample, as expected for phonon conduction. The drop in $R_B T^3$ at lower temperatures is believed to be associated with the presence of 3-ppm Mn, the only known magnetic impurity that does not have a Kondo temperature well above the temperature range of the measurements.

The Au foils were not annealed after rolling, but they were degreased before the sample was assembled. In this case the thermal time constants associated with the approach of a steady-state temperature drift following a change in heater current were long and increased with de-

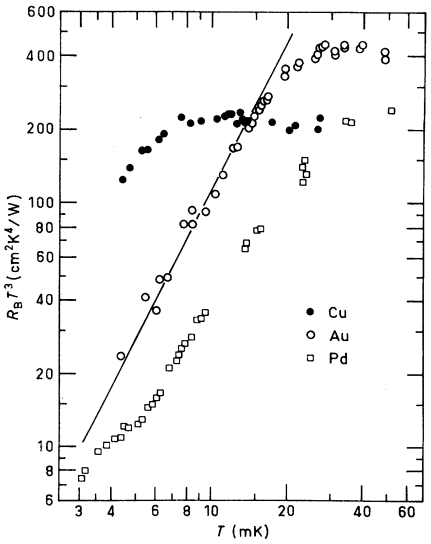

FIG. 1. The measured thermal boundary resistances, presented to demonstrate deviations from a T^{-3} temperature dependence. The straight line depicts a T^{-1} dependence of R_B.

creasing temperature, to several hours at the lowest temperatures. This effect is believed to be produced by the high nuclear heat capacity. As shown in Fig. 1, $R_B \propto T^{-1}$ at the lowest temperatures.

The lowest values of R_B were obtained for the Pd sample, which was studied in a mechanical condition similar to that of the Au sample. The temperature dependence of R_B is also similar to that of the Au sample. For the Pd sample, the effect on R_B of the addition of up to 900 ppm He^4 to the pure (5-ppm He^4) ^3He was studied. If the ^4He had been uniformly distributed over the total surface area in the cell, 900 ppm would correspond to more than a monolayer. In that case, and if the effect on R_B for the Pd sample is comparable to that observed[8] for a CMN-^3He surface, the addition of 900 ppm ^4He would have increased R_B by more than an order of magnitude at 3 mK. It seems almost certain that a monolayer of ^4He would have had a significant effect on the magnetic heat transfer and, therefore, that the ^4He was concentrated in some other part of the system. Preferential adsorption on the CMN in the cell would have produced a noticeable increase in the time constant of the CMN thermometer at the lowest temperatures, but no such effect was observed. The most probable explanation for insensitivity of R_B to the addition of ^4He is that most of the ^4He was trapped[9] in the heat exchangers of the fill line and never reached the cell.

The observed temperature dependence may be compared with an analysis of the theoretical expression [Eq. (20) of Ref. 5] given by Leggett and Vuorio for the magnetic boundary resistance determined by electromagnetic dipole-dipole interaction between the ^3He nuclei and electronic magnetic moments $g\mu_B J$. To get the most realistic values for the constants in the expression we chose them to fit the CMN-^3He experiments.[8] This gives

$$R_B^{-1} = 1.6\times10^{-6} x^{2/3} T Q_J(T) \text{ W/cm}^2 \text{ K}^2 \qquad (1)$$

with x = concentration, in atomic percent, of the magnetic moments taking part in the heat transfer and

$$Q_J(T) \simeq [\sum_m \exp(-\beta\epsilon_m)]^{-1} \sum_{\alpha=x,y,z} \sum_{mn} \exp(-\beta\epsilon_m) |\langle n | gJ_\alpha | m\rangle|^2 \beta(\epsilon_n - \epsilon_m), \qquad (2)$$

where ϵ_m and ϵ_n are energy levels of the paramagnetic ions. The sum is over the region $\beta|\epsilon_n - \epsilon_m| \lesssim 3$. We see that $Q_J(T)$ measures the magnetic fluctuation energies per impurity compared with $k_B T$. It approaches zero in both the limits $T \to 0$ and $T \to \infty$, and has a maximum value of order 1 near the transition temperature. For noninteracting spins in a magnetic field, for example, Q_J behaves as T^{-2} when $T \to \infty$ (as in the case in CMN when $T \gg 2$ mK) and as $T^{-3}\exp(-1/T)$ when $T \to 0$.

The paramagnetic ions in our samples differ from the Ce^{+3} ions in CMN in that they are randomly distributed. As a consequence, there is a wide range of transition temperatures where energy fluctuations are large and $Q_J(T)$ is only weakly temperature dependent. From Eq. (2) it follows that we should then have, approximately, $R_B \propto T^{-1}$. The same equation also gives the estimate

$$Q_J \lesssim \langle g^2 J^2 \rangle = g^2 J(J+1) \equiv p^2. \qquad (3)$$

From this expression we can calculate the effective number of Bohr magnetons, p, from the experimental values of R_B. For the Cu specimen Mn is the only impurity that is not well below its Kondo temperature and not spin compensated. We find the value $p = 4$ for Mn, which agrees well with magnetic susceptibility data[10] which give $p = 4.5$. A similar comparison applies to the impurities in Pd, for which the matrix is easily polarized—we find $p = 7$ while other measurements[11] give $p = 10$. On the other hand, the Au sample does not agree with the theory, because most of the Gd^{+3} ions are already in an ordered state. Heat capacity measurements[12] on *Au*Gd above 60 mK show the qualitative behavior (heat capacity proportional to T and approximately independent of x) expected[13] for dilute random alloys, leading to a distribution of effective fields that is independent of field. For this model $Q_J \propto T$ in contrast with our results which show practically no dependence on T. However, in that analysis the hyperfine interactions have been neglected, and they can be important if there is no large internal field that locks the electronic spins. Thus, the distribution of effective fields may increase towards smaller fields making Q_J less dependent on temperature.

In summary, considerable reductions in R_B at metal-^3He interfaces have been obtained by the addition of magnetic impurities. The results are in qualitative agreement with the Leggett-Vuorio

theory, but a detailed quantitative comparison is not possible, partly because the temperature region of interest is near and below the magnetic ordering temperatures of the alloys where the theory is more difficult to apply, and partly because the description of the magnetic systems is not known in detail. Although the values of R_B achieved do not yet make nuclear demagnetization really practical for cooling ^{3}He into the submillikelvin region, the observed temperature dependence, $R_B \propto T^{-1}$, is a significant improvement over that expected for phonon conduction, and the results are sufficiently encouraging to suggest further development. For example, in solutions of other rare earths in metals the exchange interactions are probably weaker, giving larger values of $Q_j(T)$ at low temperatures.

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Stabilizing Effect of an Electron Temperature Gradient on Collisionless Drift Instabilities

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The radial electron temperature profile of a hydrogen plasma column is controlled by electron-cyclotron resonance heating. With the use of this technique the stabilizing effect of the electron temperature gradient on collisionless drift instabilities is checked experimentally.

Drift instabilities which arise in low-β, collisionless, inhomogeneous plasmas are affected by the presence of an electron temperature gradient. Analysis of the dispersion relation shows that a gradient of the parallel electron temperature (component parallel to the confining field) provides a stabilizing influence on the electron drift instability if it points in the direction of the radial density gradient.[1,2] In this Letter, we describe an experimental investigation of this effect.

Collisionless drift instabilities[3] have already been studied in the hydrogen plasma of the ODE device.[4] The 5.4-m-long plasma column has a density in the range 10^9–10^{10} cm^{-3}, a peak electron temperature of 10 eV, averaged ion temper-