Anomalous electrical resistivity of potassium below 0.35 K

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(Received 4 November 1981)

Ultra-high-precision measurements of the resistivity of potassium to 70 mK reveal a closely T^2 variation from 1 K down to about 0.35 K, below which the variation is slower than T^2. The T^2 behavior is consistent with simple electron-electron scattering with a mean coefficient of 2.4 ± 0.2 fΩ m/K^2. The slower variation below 0.35 K represents new anomalous behavior which is not yet understood.

Potassium is generally believed to be the simplest metal for which to calculate electronic transport properties, because of its nearly spherical Fermi surface. Indeed, the electrical resistivity of potassium due to electron-phonon scattering has been calculated with no adjustable parameters[1] and agrees with experiment to within a few percent from the melting point down to a few degrees kelvin. In contrast, some low-temperature *magneto*transport properties of potassium are highly anomalous, and there is disagreement as to the source of these anomalies. Explanations range from postulated inhomogeneities within the samples[2] to charge-density waves.[3] The possibility of the presence of charge-density waves in potassium has generated considerable interest in the study of its low-temperature properties, since the existence of such waves would be of fundamental importance for the theory of pure metals.

The behavior of the temperature-dependent portion of ρ, the zero-magnetic-field resistivity of potassium, from 2 down to 0.5 K has recently been the source of controversy, both as to the power-law variation of the data with temperature T, and its interpretation. Again, charge-density waves figure prominently in the controversy. Experiments have reported variations of (a) T^m with $1 \leq m \leq 2$,[4] (b) $T^{3/2}$,[5] and (c) $T^{2.0}$.[6] These differing forms have led to alternative explanations in terms of (1) simple electron-electron scattering,[4] which predicts an AT^2 variation with A insensitive to sample history; (2) electron-electron scattering in the presence of dislocations, which also predicts AT^2, but with A a function of the relative importance of dislocation scattering to impurity scattering[7]; (3) effects due to sample thickness, which should lead to size effects[5]; and (4) electron-phason (i.e., charge-density-wave) scattering, which was proposed to explain a $T^{3/2}$ variation.[8]

There are several difficulties with these published measurements. First, one cannot reliably correct for the presence of electron-phonon scattering between 2 and 1 K,[9] below which it becomes negligible. Since the T^m and T^2 behaviors were determined from data extending down to only 1.1 K, both must be considered suspect. Additionally, these behaviors were found using samples constrained in plastic tubing, and such constraints are believed to cause problems.[10] The data are reported to vary as $T^{3/2}$ extended down to 0.5 K, but in the crucial region below 1 K the scatter in these data is too large to permit an unambiguous discrimination between $T^{3/2}$ and T^2 variations. Finally, each investigator studied samples of only a single diameter, so that no information was obtained about size effects.

Clearly, what is needed to resolve these experimental and theoretical differences are measurements (a) to still lower temperatures to eliminate any complications due to electron-phonon scattering while providing a temperature range wide enough for an unambiguous discrimination between T^2 and $T^{3/2}$ variations; (b) of higher precision, to allow resolution of the smaller changes in resistivity which will occur at lower temperatures; (c) on samples of different diameters; and (d) on unconstrained samples.

In this Communication we describe measurements extending down to 70 mK, with precisions of 0.1 ppm, on free-hanging potassium samples with diameters ranging from 0.9 to 3.0 mm.

Our samples were prepared from high-purity potassium supplied by Mine Safety Appliances, Ltd., the source used by most previous investigators. The samples were in the form of bare wires, hanging loosely, and supported only at their ends. To avoid contamination, they were melted and handled in the purified atmosphere of a glove box, in which they were extruded through stainless steel dies into wires of diameter 0.9, 1.5, and 3.0 mm. Each sample holder contained two nearly identical pieces of potassium, one as a sample and the other as a reference resistor. Potassium potential leads were cold welded to each sample, about 5 cm apart. The potentiometer circuit employed a superconducting quantum interference device (SQUID) null detector. While in the glove box, the samples were sealed in a copper vessel which was then transferred to the cryostat. Two samples were measured soon after mounting and then two weeks and three months later, respectively. In

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TABLE I. Sample parameters. To determine A, we assumed $\rho_0 = \rho_{4.2} - 2.8$ pΩ m. τ is the time after extrusion.

Sample	Diameter (mm)	τ (days)	$\rho_{4.2\,K}$ (pΩ m)	A (fΩ m/K^2)
K4a	3.0	2	14.1	2.4
K4b	3.0	85	17.7	2.4
K5	1.5	4	18.5	2.5
K6a	0.9	1	20.2	2.3
K6b	0.9	12	19.6	2.2

each case, the temperature-dependent resistivity remained unchanged to within experimental uncertainty. Table I lists the parameters of all the samples to be discussed.

We measured the ratio of the resistance of the sample to that of the reference, as described elsewhere.[11] The currents used were 25 and 50 mA. The ratios were measured with a precision and reproducibility of 0.1 ppm, at least 10 times better than previously achieved in potassium below 1 K.[5] Current independence was checked to the same precision. Absolute resistivities at 4.2 K were determined with an absolute uncertainty of a few percent from measurements of the room-temperature and 4.2-K resistances of the sample, using $\rho_{295\,K} = 7.19$ $\mu\Omega$ cm.[12]

In even the highest-purity potassium available, the resistivity below 1 K is strongly dominated by the residual resistivity ρ_0 due to scattering from "residual" impurities. To eliminate this unknown parameter, we measure[11] the quantity $(1/\rho)(\Delta\rho/\Delta T) = \Delta \ln\rho/\Delta T$ and analyze our data in that form.

Because of our high measuring precision, the uncertainty in $\Delta \ln\rho/\Delta T$ was dominated, except at the very lowest temperatures, by the uncertainty in the temperature scale. Before these measurements, our germanium resistance thermometer was recalibrated in a manner described elsewhere.[11,12] After the measurements, the product $T\Delta T$ was checked by means of Lorenz ratio measurements using a Ag (0.1 at.% Au) alloy. We estimate that T is accurate to within 1% (usually much less) at all temperatures, and that the values of ΔT used to calculate $\Delta \ln\rho/\Delta T$ are uncertain to 1% for $0.09 \leq T \leq 0.8$ K and about 3% for $T \leq 0.09$ K and $0.8 \leq T \leq 1.3$ K. These accuracies were essential for precise determination of the temperature dependence of the data.

Figure 1 shows $R_s(T)/R_r$ (0.2 K) vs T^2 for $T \leq 0.3$ K for our sample K6 as initially measured (K6a) and as remeasured two weeks later (K6b). $R_s(T)$ is the resistance of the sample at temperature T and R_r (0.2 K) is that of the reference resistor at 0.2 K. Figure 1 illustrates (1) the achieved precision of better than 0.1 ppm and its necessity for resolving the small changes which occur at the lowest temperatures; (2) the reproducibility of the temperature-dependent portion of $R_s(T)$ at different times; and (3) a slower than T^2 variation in this temperature range.

Figure 2 shows $(\rho_{4.2\,K}/T)(\Delta \ln\rho/\Delta T)$ vs T for $T \leq 1.2$ K for samples K4a, K4b, K5, K6a, and K6b. If ρ varied exactly as T^2, then for each sample the data of Fig. 2 would fall on a horizontal straight line. The data fall closely on such lines down to about 0.35 K, below which deviations occur. Alternatively, if ρ

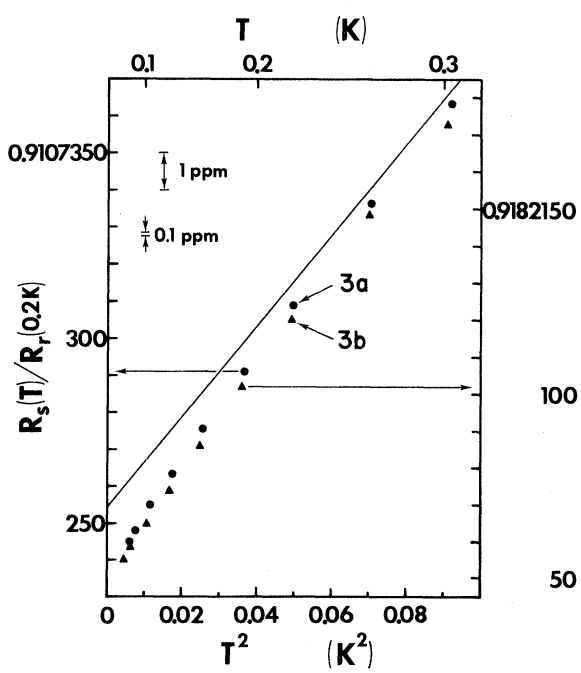

FIG. 1. $R_s(T)/R_r(0.2\text{ K})$ vs T^2 for samples K6a (●) and K6b (▲) below 0.3 K. The left-hand scale is for K6a; the right-hand scale for K6b. Note the measuring precision (0.1 ppm) and the deviation of the data from the straight line which represents a T^2 fit to the K6a data above 0.35 K.

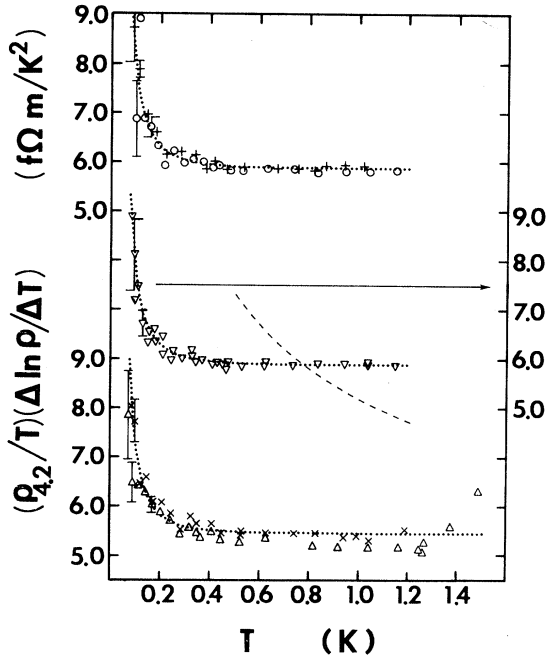

FIG. 2. $(\rho_{4.2\,\mathrm{K}}/T)(\Delta \ln\rho/\Delta T)$ vs T for samples K4a (+), K4b (○), K5 (▽), K6a (×), and K6b (Δ). The dotted curves for samples K4a, K4b, K5, and K6a represent fits to Eq. (1). The dashed curve represents a fit of $\rho-\rho_0 \propto T^{3/2}$ to the data of sample K5 from 0.5 to 1.2 K. Below ~0.2 K, error bars indicate the random uncertainties in the ordinates for various data points; above ~0.2 K, the random uncertainty is ±2%.

varied as $T^{3/2}$, as proposed by Rowlands *et al.*[5] for $T \geqslant 0.5$ K, then our data should have followed the dashed line shown for sample K5. They do not. This lack of a $T^{3/2}$ variation, coupled with the nearly T^2 behavior above 0.35 K, means that there is no need to invoke electron-phason scattering to explain our data above 0.35 K. Similarly, the absence of any significant size effect in our data eliminates size-dependent electron-electron scattering as the fundamental source of the observed behavior. In terms of published models, this leaves as possible explanations for our data above 0.35 K only simple electron-electron scattering or electron-electron scattering in the presence of dislocations.

If we use the horizontal portions of the data of Fig. 2 to determine coefficients A in resistivities of the form AT^2, we obtain the values listed in Table I. These values are (1) practically independent of sample diameter; (2) in good agreement with the value extrapolated from measurements on potassium-rubidium alloys[13]; and (3) also in good agreement with theoretical estimates for simple electron-electron scattering in pure potassium.[14,15]

Alternatively, to be consistent with the published model of dislocation-influenced electron-electron scattering,[7] our samples would require substantial dislocation scattering relative to impurity scattering, since our coefficients A lie in the moderately high-dislocation regime of that model. However, it is unlikely that a high-dislocation density would be produced by cooling strains, because our samples were unconstrained and slowly cooled to 4.2 K. It is also unlikely that a high-dislocation density existed prior to cooling, since extended annealing at room temperature left our data essentially unchanged and dislocations are believed to anneal out of potassium below room temperature.[16]

Above 0.35 K, therefore, our data are best interpreted in terms of simple electron-electron scattering. Such scattering, however, does not explain the deviations from T^2 behavior observed below 0.35 K.

To quantify the behavior shown in Fig. 2, we have tried to parametrize our data in various ways. The best fits were achieved with

$$\rho-\rho_0=(A'T^2+ET^{-0.3})(\rho_0/\rho_{4.2\,\mathrm{K}}) \quad . \tag{1}$$

The dotted lines in Fig. 2 were determined by fitting samples K4a, K4b, and K5 to Eq. (1) as a group, and by fitting sample K6a with the same value of E as for these samples but with a different value of A'. An equation of the form $(A'T^2+F\ln T)(\rho_0/\rho_{4.2\,\mathrm{K}})$ gave almost as good fits as those shown. We examined the possibility of a Kondo-like effect by measuring the thermoelectric properties of our samples. No thermoelectric anomalies were found.

The deviation from T^2 behavior is thus a puzzle. It could indicate (a) a change in the coefficient A in potassium below 0.35 K, (b) that a new phenomenon is appearing below 0.35 K, or (c) that the success of simple electron-electron scattering in describing our data above 0.35 K is fortuitous. Concerning the third alternative, we note that simple electron-electron scattering cannot explain the variations in the coefficients A seen by previous investigators.[4–6] It, therefore, cannot be a complete explanation for what has so far been reported on the low-temperature resistivity of potassium.

We plan to extend these experiments by testing whether dislocations perturb either the form or magnitude of the data, whether dissolved gases such as argon and helium perturb the data, and by studying the anomalous behavior to still lower temperatures. Thus we are constructing a system for deforming potassium samples *in situ* at 4.2 K, and are attempting to produce samples with lower ρ_0 and with and without dissolved gases.

ACKNOWLEDGMENTS

This work was supported in part by NSF Grants No. DMR-80-05865 and No. DMR-78-07892.

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