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Scaling of the magnetoresistance of UBe_{13} under pressure

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We report magnetoresistance measurements of the heavy electron compound UBe_{13} above the superconducting transition temperature T_c and below 4 K for pressures P up to 19 kbar and for magnetic fields H up to 9 T. We observe strong negative magnetoresistance at all pressures and temperatures. The resistivity ρ is quadratic in temperature T from T_c up to a maximum temperature of 1 K at 1 bar increasing to 2 K at 19 kbar. The slope of the T^2 term decreases with both H and with P. We find that $\delta(H) \equiv -[\rho(H) - \rho(0)]/\rho(0)$ for a given pressure scales as a function of H/T and exhibits power-law behavior over one decade with an exponent of 1.7. In addition, $\delta(H)$ at high pressure shows this same power law over a more limited H/T range.

INTRODUCTION

The compound UBe_{13} (Ref. 1) is one of a class of materials known as heavy fermion or heavy electron compounds.[2] These systems are characterized by Curie–Weiss (local moment) susceptibility χ at high temperatures and Pauli (itinerant) magnetic behavior at low temperature. Accompanying this change in magnetic properties is an enormous enhancement of the electronic specific heat coefficient $\gamma(T)$ $[\equiv C(T)/T]$, which is proportional to the effective electron mass, as the temperature approaches zero. Heavy electron compounds at low temperatures have been proposed to be Kondo lattice systems.[3] At high temperatures, each local moment is independent and becomes partially screened by antiferromagnetically oriented conduction electrons as the temperature is decreased; this moment compensation is complete at temperatures well below the Kondo temperature T_K. A Kondo lattice is not just the sum of the independent Kondo sites described above, but it includes correlations among the sites. This results in a decrease in the resistivity ρ below T_K in contrast to the constant, saturated ρ for the isolated Kondo impurity in the same temperature regime. The resistivity of UBe_{13} shows the classic Kondo resistivity at high temperatures that increases to a shoulder near 20 K and a peak near 2.5 K, below which ρ falls rapidly with decreasing T until at about 0.9 K, the material becomes superconducting.

The magnetoresistivity of UBe_{13} is large and negative with a strong temperature dependence. Below 1 K and for H greater than about 1 T, the data can be described by $\rho = \rho_0 + AT^2$, composed of a residual scattering term ρ_0 and a T^2 contribution that suggests a Fermi liquid ground state for UBe_{13}. At zero field, the ρ_0 value is about 100 $\mu\Omega$ cm, much larger than might be expected for nonmagnetic impurity scattering. Indeed, ρ_0 decreases almost an order of magnitude in high fields, strongly supporting its source as Kondo (magnetic) scattering. The T^2 term also shows an overall decrease with field.

Pressure P has an effect similar to field on the resistivity of UBe_{13}.[4,5] The 2.5-K peak in ρ shifts to higher temperatures, and the low-temperature resistivity is depressed in magnitude, as are ρ_0 and A. The superconducting transition temperature T_c was found to decrease at a rate of 16 mK/kbar. Specific heat measurements[6] demonstrate a 30% reduction in γ between 0 and 9.3 kbar, indicating a substantial decrease in the electronic mass, or equivalently, in the renormalized electronic density of states at the Fermi level. In contrast, recent dc susceptibility (χ) measurements[7] in this same pressure region show less than a 10% decrease from $\chi(P=0)$, suggesting much smaller changes in the electronic mass. Magnetoresistance data at high pressures can provide additional insight into the possible energy scales and into the properties of the Kondo impurity and Kondo lattice models of UBe_{13}. We report here on measurements of ρ as a function of temperature (0.15–4 K), magnetic field (0–9 T), and pressure (0–19 kbar).

EXPERIMENT

Polycrystalline UBe_{13} was prepared by arc melting together stoichiometric amounts of U and premelted Be. Measurements were performed in a self-clamped Cu-Be cell[8] using a conventional four-lead, phase-sensitive ac resistance technique. The current, which was 0.07 A cm^{-2} or smaller to avoid Joule heating, was roughly parallel to the applied magnetic field. The pressures were determined from the T_c of a Sn manometer.[9] Temperatures were determined with a Speer carbon radio resistor that was calibrated against a germanium resistor at zero field and was corrected[10] for magnetoresistance at finite fields.

RESULTS AND DISCUSSION

Resistivity ρ vs temperature T data at 9.9 kbar are presented in Fig. 1. A large negative magnetoresistance is apparent in this temperature range, similar to previously reported zero pressure measurements on UBe_{13} (Refs. 11–13). It is clear that the magnetoresistance is a complicated function of T and H, and furthermore, it is not possible to determine $\rho(H) - \rho(0)$ explicitly below $T_c(H=0)$ as $\rho(0)$ is shorted by the superconducting electrons. If the data of Fig. 1 are plotted versus T^2, there are extensive regions below 1 K for which ρ can be modeled as $\rho_0 + AT^2$, as can be seen in

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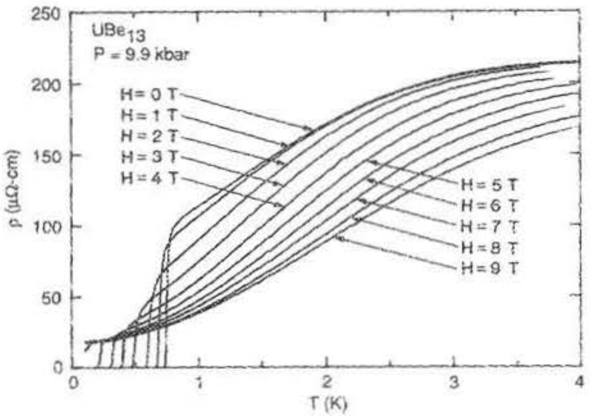

FIG. 1. Resistivity ρ vs temperature T for UBe$_{13}$ at 9.9 kbar.

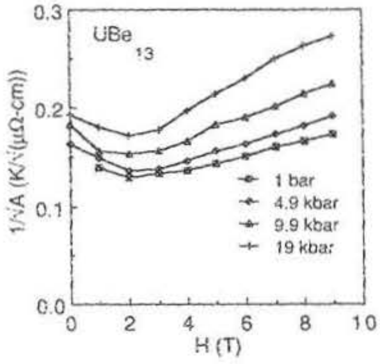

FIG. 3. The coefficient of A, the quadratic term in the low-temperature resistivity of UBe$_{13}$, plotted as $1/\sqrt{A}$ vs magnetic field H for the pressures indicated. The lines are only guides to the eye.

Fig. 2. The extent of the T^2 region increases with field and also with pressure. At 9 T it extends up to $\simeq 1$ K at $P = 0$ and up to $\simeq 2$ K at $P = 19$ kbar. For H less than about 3 T, the smaller range for which ρ has a T^2 temperature dependence leads to less accurate values of ρ_0 and A than at higher fields.

In a Fermi liquid picture, the low-temperature resistivity is proportional to $(T/T^*)^2$, where T^* is a characteristic temperature of the system. We then make the identification that A is proportional to $(1/T^*)^2$, and therefore $A^{-1/2}$ is proportional to T^*. Values of $A^{-1/2}$ have been extracted from fitting the data in Fig. 2 and from the data at other pressures. The behavior of $A^{-1/2}$ as a function of H and P is shown in Fig. 3. The initial decrease in $A^{-1/2}$ ($\propto T^*$) for H less than 2–3 T is not understood.[4] At higher fields, $A^{-1/2}$ increases approximately linearly with H. This rate of change ($d \ln A^{-1/2}/dH$) varies from 6.3%/T at 1 bar to 14%/T at 19 kbar. Remenyi *et al.*[11] were unable to fit their data below 5 T to a $\rho_0 + AT^2$ form. In addition, they observed a distinct break in the ρ vs T^2 data near T_c ($H = 0$). Their $A^{-1/2}$ values increase monotonically with field but are a factor of 1.4 smaller (A is a factor of 2 larger) than seen here. This may be related to their high-field ρ value of 40 $\mu\Omega$ cm, twice as large as in the present work.

In both the data of Fig. 2 and in the corresponding data at other pressures (not shown), there appears to be a limiting, high-field, pressure-independent residual resistivity ρ_0. By extrapolating the resistivity to $T = 0$ K with a T^2 temperature dependence, ρ_0 values have been obtained and are shown in Fig. 4. The accuracy of these values improves with both H and P, i.e., with the length of the T^2 region and the decrease in the length of the extrapolation; a typical error bar is about 2%. A limiting high-field, residual resistivity ρ_0 value of 18 ± 1 $\mu\Omega$ cm, which is independent of pressure, is obtained from the data in Fig. 4. This value is in good agreement with the zero pressure ρ_0 of $\leqslant 17$ $\mu\Omega$ cm reported by Rauchschwalbe, Steglich, and Rietschel,[13] but is a factor of 2 smaller than that observed by Remenyi *et al.*,[11] indicating the possible better quality of the first two samples. We believe that this ρ_0 is representative of intrinsic (nonmagnetic) scattering in the UBe$_{13}$ host lattice, such as substitutional, vacancy, or grain-boundary scattering.

The large, negative magnetoresistance attaining a maximum at $T = 0$ is a general property of dilute (independent) Kondo impurities, such as Ce in LaB$_6$.[14] This behavior can be described quantitatively by the Bethe–Ansatz solution of the $S = 1/2$ Coqblin–Schrieffer model for independent Kondo impurities.[15] This model has been successfully applied to CeAl$_3$ and CeCu$_2$Si$_2$ (Ref. 16) as well as to UBe$_{13}$ (Refs. 12 and 16) at ambient pressure. In the Ce-based com-

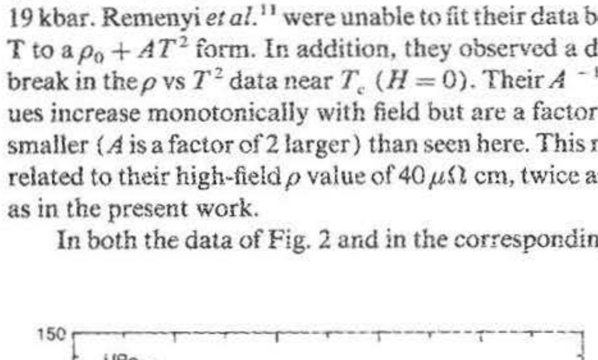

FIG. 2. Resistivity ρ vs temperature squared for UBe$_{13}$ at 9.9 kbar and for $T < 1$ K.

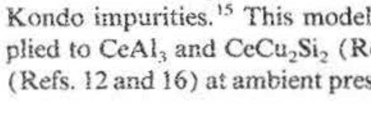

FIG. 4. The residual resistivity ρ_0 vs magnetic field H for the pressures indicated. The lines are only guides to the eye.

pounds, there is clear evidence of a change in sign of the magnetoresistance at a temperature in coincidence with a maximum in $\gamma(T)$ and a sign change in the thermopower. Below this temperature T_0, it is believed that a coherent ground state (the Kondo lattice) has fully developed. Such direct observations have not yet been made for UBe_{13}, although the application of the above-mentioned $S = 1/2$ Coqblin–Schrieffer model suggests a T_0 of 0.1–0.2 K. This temperature is about 10% of T_{max} ($= 2.5$ K), the position of the maximum in ρ, below which UBe_{13} is beginning to enter the Kondo lattice regime. T_{max} increases with pressure linearly up to 6.9 K at 19 kbar. Additionally, the extent of the T^2 region and $A^{-1/2}$ increase and $\rho(0)$ decreases with increasing pressure, all indicating a closer approach to the coherent state. If T_0 increased proportionately to T_{max}, then it might be as high as 0.25–0.50 K at 19 kbar. However, no clear evidence of a sign change in the magnetoresistance was observed in the present experiment. Measurements at significantly higher pressures (40–100 kbar) are in progress to address this question.

In Fig. 5, the normalized magnetoresistivity $\delta(H) \equiv -[\rho(H) - \rho(0)]/\rho(0)$ has been plotted versus H/T for pressures of 1 bar and 19 kbar and temperatures between 0.7 and 4.0 K. The scaling apparent in these data indicate that $\delta(H)$ is a universal function of H/T at a given pressure. Similar results are obtained at 4.9 and 9.9 kbar. The linear regions in the log-log plot shown in Fig. 5 imply a power-law dependence of the form $\delta(H) = a + bH^c$ where $c = 1.68 \pm 0.05$. Attempts to scale the data with $H/(T + \Theta)$ showed significant deviations for $|\Theta| > 0.1$ K in disagreement with the results of Remenyi *et al.*[11] ($\Theta = 1$ K), but in good agreement with Batlogg *et al.*[12] and Rauchschwalbe.[16] The lower limit in H/T over which this power law is valid increases slowly with P, but the upper limit is relatively pressure independent. At high values of H/T and for all pressures studied, the normalized magnetoresistivity saturates at 60%–70%.

CONCLUSIONS

In summary, we find a large, negative magnetoresistance in UBe_{13} for T less than 4 K, H less than 9 T, and P less than 19 kbar. The resistivity at $T = 0$ K decreases rapidly with field and pressure reaching a lower limit of 18 $\mu\Omega$ cm. The resistivity has an AT^2 dependence over a temperature region that increases with field and with pressure. $A^{-1/2}$, which is proportional to a characteristic temperature of the system, increases with H and with P. All these features are manifestations of independent Kondo scattering in the temperature region for which intersite correlations are beginning to develop, but no evidence of Kondo lattice formation was observed in the present work. The normalize magnetoresistivity $\delta(H)$ scales as a function of H/T with the same $(H/T)^{1.68}$ power-law dependence observed over part of the range for all the pressures studied.

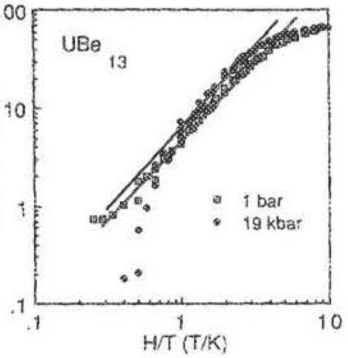

FIG. 5. Normalized magnetoresistance of UBe_{13}, $-[\rho(H) - \rho(0)]/\rho(0)$ vs magnetic field divided by temperature H/T for 1 bar and for 19 kbar. Included are values for temperatures between 1 and 4 K for both pressures and at 0.7 K for 19 kbar. The lines are only guides to the eyes.

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