Effect of pressure and magnetic field on the electrical resistivity of UBe_{13}

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The electrical resistivity ρ of the heavy-electron superconductor UBe_{13} has been measured at temperatures T between 0.1 and 300 K for pressures P to 16 kbar and in magnetic fields H up to 9 T. The temperature T_{max} at which ρ shows a maximum increases linearly with P at $H=0$ and with H^2 for $P=14.8$ kbar. The resistivity, when normalized to its value at $T_{max}(P)$, scales as a function of reduced temperature $T/T_{max}(P)$ from 1 K to $\sim 1.4T_{max}$. At $P=14.8$ kbar, the magnetoresistance $-[R(H)-R(0)]/R(0)$ behaves as a universal function of H/T for $1 \leq T \leq 6$ K and $0 < H < 8$ T. For pressures greater than ~ 9 kbar, the resistivity increases quadratically with temperature. The T^2 coefficient of resistivity decreases monotonically with increasing P at $H=0$ but shows a nonmonotonic variation with H, passing through a maximum near 3 T.

I. INTRODUCTION

The compound UBe_{13} belongs to the class of heavy-electron materials that are distinguished by enormous electronic specific-heat coefficients γ that attain values as large as $\sim$ 1J/mol-K^2 and it is one of the few compounds within this class that exhibits superconductivity.[1] A great deal of effort has been expended in characterizing the many anomalous physical properties of UBe_{13} in both the normal and superconducting states.[2] A useful method of investigating the underlying mechanisms responsible for the remarkable physical characteristics is to determine the response of these properties to variable external parameters such as pressure P or magnetic field H.

Measurements of the superconducting critical temperature T_c of UBe_{13} as functions of P up to ~ 10 kbar at $H=0$ (Ref. 3) and H up to 10 T at $P=0$ (Ref. 4) have been reported. In addition, the electrical resistivity ρ,[4-6] magnetization,[7] and specific heat,[6,8] have been measured to fields of 10, 9, and 13 T, respectively, at ambient pressure. Recently, the specific heat of UBe_{13} has been determined[9] at $H=0$ for $0.2 < T < 20$ K as a function of pressures to ~ 9.4 kbar. Interestingly, pressure and magnetic field have qualitatively similar effects on the overall shape of C_p versus T: namely, a suppression of C_p for $T \lesssim 2$ K and an enhancement of the specific heat at higher temperatures. Both pressure and field move the specific-heat maximum near 2 K to higher temperatures and drive $\gamma(T=0)$ to smaller values.

Here we report results of measurements of the resistivity between 150 mK and 300 K at pressures up to 16 kbar and in magnetic fields to 9 T.

II. EXPERIMENTAL DETAILS

Polycrystalline UBe_{13} was prepared by arc melting the high-purity constituents under an argon atmosphere in a manner described previously.[1] The quality of this sample is reflected in its high $T_c \simeq 0.905$ K and very sharp inductive transition width $\Delta T_c = 0.030$ K. Resistivity measurements under pressure were performed in Be-Cu self-clamping piston-cylinder devices in a ^{4}He cryostat for temperatures between 1 and 300 K (Ref. 10) and in a ^{3}He-^{4}He dilution refrigerator for $0.15 < T < 2$ K. Separate but qualitatively similar pressure cells were used in the two different temperature regimes with the same sample being common to both experiments. A 1:1 mixture of isoamyl alcohol and n-pentane served as the quasihydrostatic pressure medium, and the pressure was inferred from the T_c of superconducting Pb in the case of measurements above 1 K and of Sn for measurements below 1 K.[11] The ac electrical resistance was measured using a standard four-lead phase-sensitive detection technique at a frequency of 229 Hz.[10] On the basis of a room-temperature electrical *resistivity* of 107 $\mu\Omega$ cm for UBe_{13}, a geometrical factor was calculated for this sample and used to convert the measured resistance to resistivity. Above 1 K, the temperature was determined by a calibrated carbon glass thermometer and from a Speer resistance thermometer for those experiments in the dilution refrigerator. Magnetic fields to 9 T were produced by superconducting solenoids, with the field direction roughly parallel to the measuring current. Magnetoresistance effects in the carbon glass and Speer thermometers were taken into account when determining temperatures from them in the presence of a magnetic field.

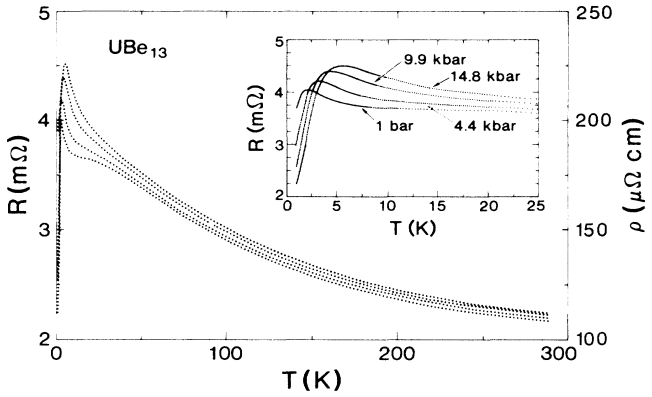

FIG. 1. Electrical resistance R and resistivity ρ versus temperature T of UBe_{13} at pressures of 1 bar, 4.4, 9.9, and 14.8 kbar. The inset provides an expanded view of these curves below 25 K.

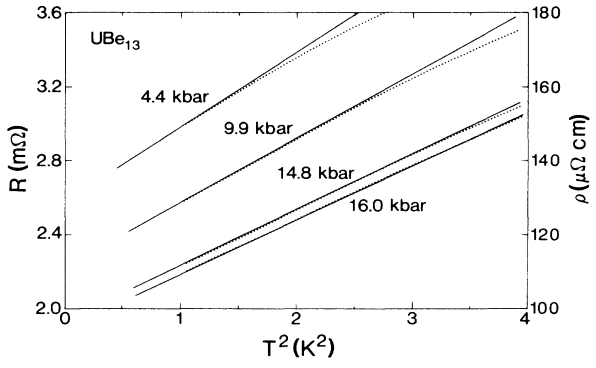

FIG. 3. Electrical resistance R and resistivity ρ versus temperature squared T^2 for UBe_{13} at pressures of 4.4, 9.9, 14.8, and 16.0 kbar. Straight lines have been drawn to indicate the interval over which the data are linear.

III. RESULTS

Shown in Fig. 1 is the resistance R (and resistivity calculated as discussed in Sec. II) as a function of temperature for UBe_{13} between 1 and 300 K at pressures of 1 bar, 4.4, 9.9, and 14.8 kbar. Apparent in Fig. 1 is a rather strong effect of pressure on $R(T)$, particularly below ~ 25 K. Most notable is a pressure-induced increase of the temperature T_{max} at which R attains its maximum value, an increase in the magnitude of $R(T_{max})$, and a strong suppression of the resistivity for some $T < T_{max}(P=0)$. A plot of T_{max} versus P (Fig. 2) reveals a linear increase in T_{max} with applied pressure at a rate of 0.23 K/kbar. For pressures greater than ~ 4.4 kbar the resistivity near 1 K appears to increase quadratically with temperature over a limited temperature interval that increases with pressure (see Fig. 3). At the lowest pressure (4.4 kbar) this temperature regime is constrained to a very small region near 1 K and the presence of a quadratic power law in $R(T)$ should be considered with justifiable skepticism; but by 16 kbar, $R(T)$ is clearly proportional to T^2 up to ~ 2 K. The slope $dR/dT^2 \equiv A$ decreases monotonically with increasing pressure, having the functional relationship

$$A^{-1/2} = \alpha + \beta P \ , \tag{1}$$

where $\alpha = 0.21$ $(\mu\Omega\,\mathrm{cm}/K^2)^{-1/2}$ and $\beta = 0.0034$ $(\mu\Omega\,\mathrm{cm}/K^2)^{-1/2}$/kbar, as shown in Fig. 4.

Results obtained from measurements of $R(T)$ on UBe_{13} at 14.8 kbar in various fixed magnetic fields to 8 T are presented in Fig. 5. Similar to previously reported magnetoresistance measurements on UBe_{13} at zero pressure,[4,6,8] we find a large, negative magnetoresistive effect in UBe_{13} for $1 \leq T \leq 20$ K, and an increase in T_{max} with increasing field. The data of Fig. 5 may be plotted as isotherms in the form $-[R(H)-R(0)]/R(0)$ versus H as shown in Fig. 6. In this log-log plot, all of the curves are linear in the range $-[R(H)-R(0)]/R(0) \lesssim 10\%$ with a common slope of ~ 1.6 and exhibit a tendency to saturate at higher values of $-[R(H)-R(0)]/R(0)$ to a constant value of

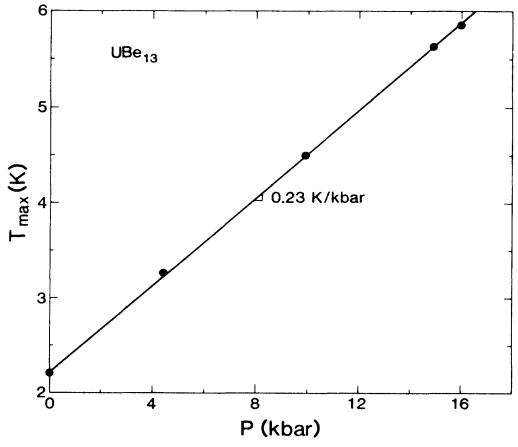

FIG. 2. Temperature of the resistance maximum T_{max} in UBe_{13} as a function of applied pressure P.

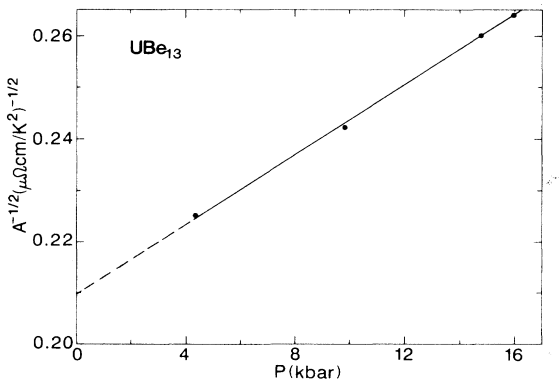

FIG. 4. $A^{-1/2}$ versus pressure P, where A is the coefficient of the T^2 term of the low-temperature electrical resistivity for UBe_{13}.

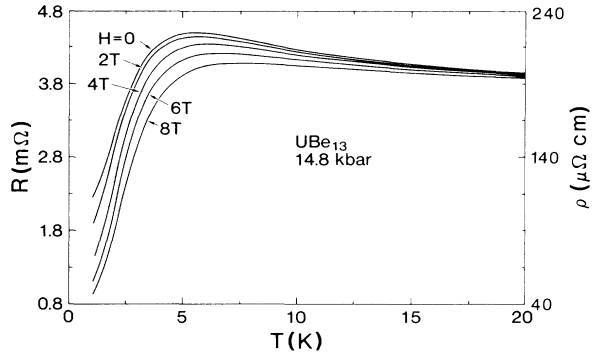

FIG. 5. Electrical resistance R and resistivity ρ versus temperature T for UBe_{13} at 14.8 kbar in applied magnetic fields of 0, 2, 4, 6, and 8 T.

$\gtrsim 60\%$. The approach to saturation is most evident for the lowest temperature (1.03 K) isotherm, which indicates that the resistivity is nearing a field independent value at the lowest temperatures and highest fields.

The data of Fig. 6 suggest that the magnetoresistance might be described by a universal function. To determine the form of this functional dependence, the magnetoresistance data have been plotted in Fig. 7 as $-[R(H)-R(0)]/R(0)$ versus $H/F_S(T)$, where $F_S(T)$ is a numerical scaling factor chosen for each isotherm such that the data conformed to the universal curve shown. Values of $F_S(T)$ so determined are plotted in the inset of Fig. 7 as a function of temperature. For $T \lesssim 6$ K, $F_S(T)$ is a linear function of temperature and passes through the origin, indicating that for this temperature range the magnetoresistance is a universal function of H/T. Interestingly, this simple scaling behavior becomes more complex for $T \geq T_{max}$ $(P,H=0)$. For $H/T \lesssim 3$ T/K, the magnetoresistance can be written as

$$-[R(H)-R(0)]/R(0)=\eta+\xi(H/T)^{1.6}\,, \tag{2}$$

with $\eta=0.015$ and $\xi=0.05$ $(\mathrm{T/K})^{-1.6}$.

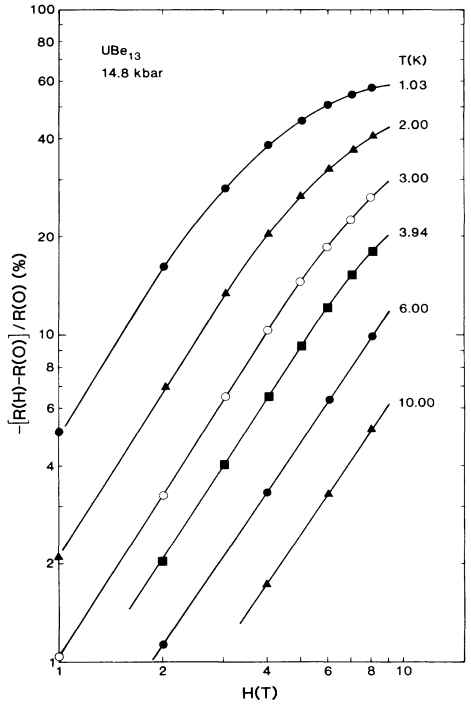

FIG. 6. $-[R(H)-R(0)]/R(0)$, where R is the field-dependent electrical resistance, versus applied magnetic field H isotherms for UBe_{13} at 14.8 kbar. The linear portion of each isotherm has a slope of ~ 1.6.

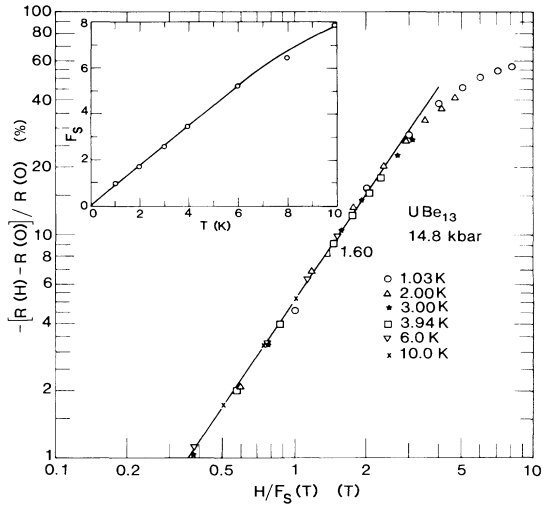

FIG. 7. Log $\{-[R(H)-R(0)]/R(0)\}$ versus log $[H/F_S(T)]$ isotherms for UBe_{13} at 14.8 kbar. The data are the same as those in Fig. 6 except that here the field has been scaled by a temperature dependent scaling factor $F_S(T)$ whose variation with temperature is displayed in the inset.

The effect of a magnetic field on the low-temperature resistance of UBe_{13} at 14.8 kbar is shown in Fig. 8 where R versus T^2 is plotted for various fixed magnetic fields. Like pressure, magnetic field has the effect of increasing the low temperature range in which $R\alpha AT^2$. Values of the T^2 coefficient A obtained from these curves are plotted in Fig. 9 as a function of magnetic field. Clearly a nonmonotonic dependence of $A(H)$ is observed, with a maximum in A near 3 T. Similar behavior has been found from measurements of UBe_{13} at 4.9 kbar and $T<1$ K. Figure 10 shows R versus T^2 for UBe_{13} at 4.9 kbar in magnetic fields to 9 T. For fields greater than ~ 1 T, a

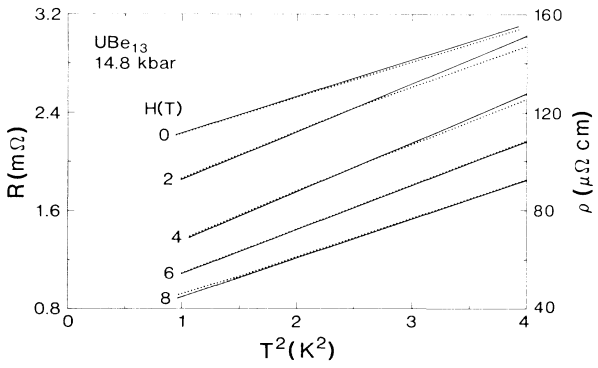

FIG. 8. Electrical resistance R and resistivity ρ as a function of temperature squared T^2 for UBe_{13} at 14.8 kbar in applied magnetic fields H of 0, 2, 4, 6, and 8 T.

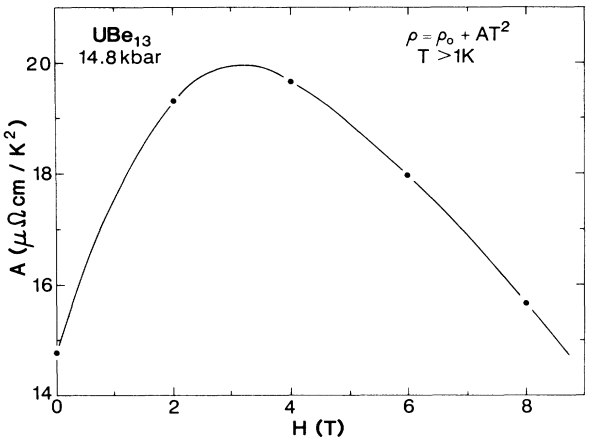

FIG. 9. Coefficient A of the T^2 term in the electrical resistivity versus applied magnetic field H for UBe_{13} at 14.8 kbar and temperatures $T \geq 1$ K.

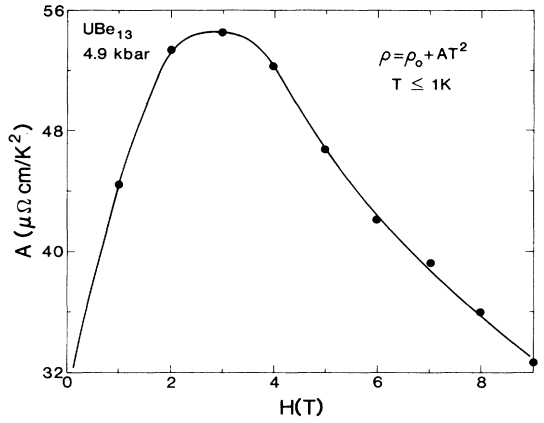

FIG. 11. Coefficient A of the T^2 term in the electrical resistivity of UBe_{13} at 4.9 kbar as a function of applied magnetic field H for temperatures $T \leq 1$ K.

quadratic temperature dependence of R is found for $T \gtrsim T_c(P)$. The field dependence of the T^2 coefficient is shown in Fig. 11. Except for an overall increase in the magnitude of $A(H)$ by about a factor of 2.5 relative to the data in Fig. 9, the qualitative dependence of A on H is similar for the two pressures, both showing a peak in $A(H)$ for $H \simeq 3$ T even though these data were determined in different temperature intervals.

IV. DISCUSSION

The temperature-dependent resistance of UBe_{13} is one of the most striking of the heavy-electron systems.[12] At high temperatures, the large value of ρ and its negative slope $d\rho/dT$ are qualitatively consistent with the idea that electron transport is dominated by incoherent spin-flip scattering normally associated with a single impurity Kondo effect. For temperatures much less than T_{max}, intersite correlations begin to become more pronounced, leading to coherence in the spin-fluctuation spectrum and presumably to Fermi-liquid behavior at sufficiently low temperatures.[13] However, under ambient conditions, the onset of superconductivity at $T_c \sim 0.9$ K masks any Fermi-liquid behavior that otherwise would be manifested in the transport properties.[14] The transition between these two extreme regimes results in a maximum in the resistivity at T_{max}. The precise mechanism responsible for the development of intersite correlations is uncertain, although Ruderman-Kittel-Kasuya-Yosida (RKKY) and quadrupolar couplings between f-atom sites have been suggested as possible sources.[15,16] What is clear in the case of UBe_{13} is that with increasing pressure the electronic excitation spectrum becomes more fully coherent for some $T < T_{max}(P=0)$, as evidenced by the rapid drop in resistivity with pressure in this temperature regime.

A low-temperature resistivity maximum is also found in the Ce-based heavy-electron compounds $CeAl_3$,[17] $CeCu_6$,[18] and $CeCu_2Si_2$.[19] The effect of pressure on T_{max} in these systems[18,20–22] is similar to that observed in UBe_{13}, namely a strong positive increase in T_{max} with pressure. In the cases of $CeCu_6$ and $CeCu_2Si_2$, it has been found that the resistance when normalized to its value at T_{max} scales as a function of $T/T_{max}(P)$ over a large low-temperature interval including T_{max}.[18,21] In Fig. 12, a

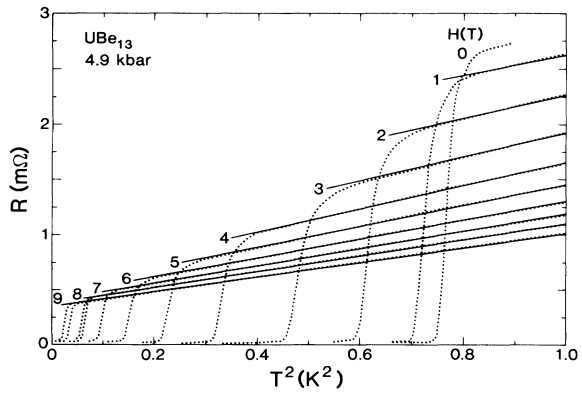

FIG. 10. Electrical resistance R versus temperature squared T^2 for UBe_{13} at 4.9 kbar in various applied magnetic fields H to 9 T for temperatures $T \leq 1$ K. The resistance drop to zero signals the occurrence of superconductivity.

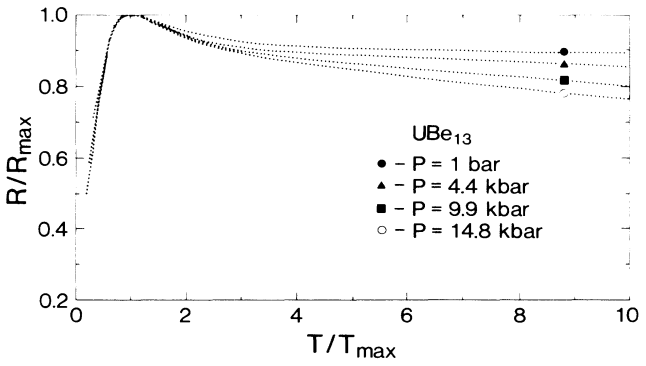

FIG. 12. Electrical resistance R of UBe_{13} normalized to its maximum value R_{max} as a function reduced temperature T/T_{max}. Data used are those given in Fig. 1.

plot of this type is shown for UBe_{13}. Like $CeCu_6$ and $CeCu_2Si_2$, R/R_{max} scales as a function of reduced temperature for $0.2 \lesssim T/T_{max}(P) \lesssim 1.4$, thereby suggesting that the resistivity maximum in these systems has a common origin. Such scaling is not limited to the examples mentioned above but has been observed in a large number of heavy-fermion or mixed-valence compounds, including URu_2Si_2,[23] $CePd_3$,[24] $CePt_2Si_2$,[25] and $CeIr_2Si_2$,[25] which show a maximum in their resistivity below room temperature. Therefore, it appears that resistivity scaling is a very general phenomenon and that T_{max} represents a fundamental energy scale in these materials.

A low-temperature resistivity proportional to T^2 in the heavy-electron compound $CeAl_3$ (Ref. 17) has prompted a description of the heavy-electron systems at very low temperatures in terms of Landau Fermi-liquid theory (Ref. 26). Such a theory provides a quite adequate model for the low-temperature transport behavior of the heavy-electron superconductor UPt_3.[27] In these theories the T^2 coefficient of resistivity A is proportional to the inverse square of a characteristic temperature $T^*[A\alpha 1/T^{*2} = (A_0^a/T_F)^2]$ (where T_F is the degeneracy temperature and A_0^a is the singlet forward scattering amplitude) that sets the energy scale for Fermi-liquid behavior. Therefore, a plot of $A^{-1/2}$ should be linear in T^*. In Fig. 13 we show $A^{-1/2}$ as a function of T_{max}, where T_{max} has been changed by pressure (Fig. 2) and the A values are those taken from Fig. 3. Given the observations that both $A^{-1/2}$ and T_{max} are linear functions of pressure (Figs. 2 and 4) this linear dependence of $A^{-1/2}$ on T_{max} is not unexpected. However, viewed alternatively and perhaps more significantly, the fact that $A^{-1/2}$ and T_{max} vary linearly with P is merely consistent with $A^{-1/2} \alpha T_{max}$. On the basis of this result alone, it is not justifiable to identify T_{max} as a Fermi-liquid parameter but it would suggest that T_{max} and T^* may be functionally related.

Before turning to further discussions, we should comment on the magnitude of A. As mentioned, under ambient conditions there is no detectable Fermi-liquid-like T^2 dependence of ρ in UBe_{13} above T_c. For $P=H=0$, the resistivity at T_c is about 130 $\mu\Omega$ cm. Recent very-high-field measurements on UBe_{13} at low temperatures suggest that the intrinsic impurity-limited residual resistivity is ~ 15 $\mu\Omega$ cm.[28] Assuming that if superconductivity were not present there would be an observable Fermi-liquid regime, then the T^2 coefficient of resistivity would have to be approximately (130-15 $\mu\Omega$ cm)/(0.9 K)^2 = 142 $\mu\Omega$ cm/K^2. This value is a factor of ~ 6 larger than estimated from the $P=0$ intercept of Fig. 4 but is qualitatively consistent with the value of $A \simeq 116$ $\mu\Omega$ cm/K^2 obtained by extrapolating to $H=0$ the field dependence of the T^2 coefficient found by Remenyi *et al.*[5] at $P=0$. However, the data of Fig. 9 would suggest that such a extrapolation might not be valid. A possible rationalization for these "inconsistencies" is that the residual resistivity is in fact large under ambient conditions but is depressed by both field and pressure. Indeed, for fields greater than about 4 T, Remenyi *et al.*[5] find the extrapolated residual resistivity to decrease strongly with increasing field strength. Therefore, a T^2 coefficient less than 100 $\mu\Omega$ cm/K^2 for UBe_{13} under ambient conditions might be expected; however, neither the results of Remenyi nor of our pressure study unambiguously define the value of A for $P=H=0$.

Both the electrical resistivity and specific heat C_p of UBe_{13} exhibit a maximum at roughly the same temperature T_{max} between 2 and 2.5 K. Similar behavior is found in the heavy-electron compound $CeAl_3$ at 35 K. Thus far, only in UBe_{13} has the effect of both pressure and magnetic field been studied on T^{ρ}_{max} and $T^{C_p}_{max}$. In each case, the maximum is moved to higher temperatures. From the field study of UBe_{13} at 14.8 kbar (Fig. 5), we find that $dT_{max}/dH^2 = 0.029$ K/T^2 (see Fig. 14). A comparison of

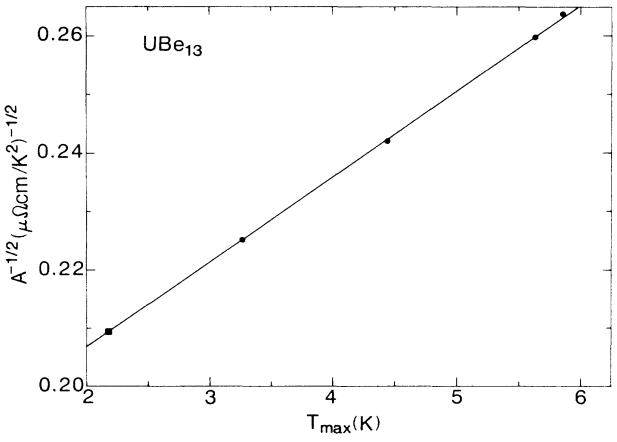

FIG. 13. $A^{-1/2}$ versus T_{max} for UBe_{13}, where A is the coefficient of the T^2 term of the low-temperature electrical resistivity and $T_{max}(P)$ is the pressure-dependent temperature of the resistance maximum. The solid square point corresponds to the value of $A^{-1/2}$ obtained from Fig. 4 by extrapolating $A^{-1/2}$ versus P to $P=0$.

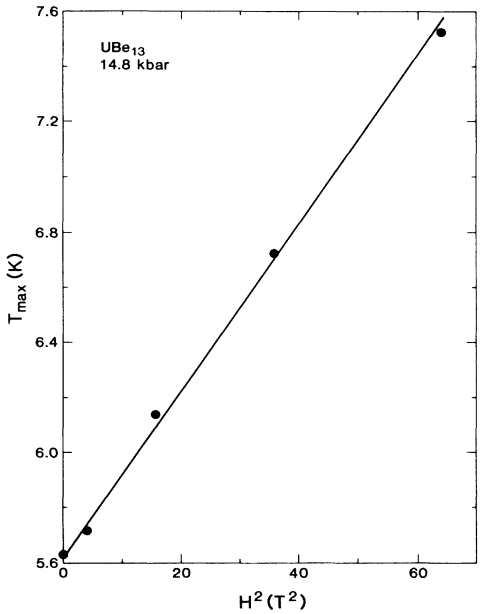

FIG. 14. T_{max}, the temperature of the resistance maximum, versus applied magnetic field squared H^2 for UBe_{13} at 14.8 kbar. The slope of the solid line is 0.029 K/T^2.

this slope with that found in Fig. 2 for the pressure dependence of T_{max} would suggest that 1 T^2 is approximately equivalent to 100 bar in terms of the corresponding effects on T_{max}. The apparent equivalence of H and P seems to be reflected in the overall shape of the specific heat at low temperatures as well.[9,29] Interestingly, a linear extrapolation of C_p/T versus T from above T_c to $T=0$ gives values of $C_p(P)/T \mid_{T=0}$ that are a nearly linear function of $1/T_{max}(P)$, where $T_{max}(P)$ is determined resistively.[15] For a single Kondo impurity, the zero-temperature Sommerfeld coefficient $\gamma_0(\equiv C_p/T \mid_{T=0})$ is related to the Kondo temperature T_K by $\gamma_0 T_K = 0.68R$, where R is the gas constant.[30] From the linear dependence of $\gamma_0(P)$ on $1/T_{max}(P)$ we find $\gamma_0 T_{max} \simeq 0.2R$, implying that $T_K \simeq 3.5 T_{max}$. How seriously this inference should be taken, given the complexity of interactions leading to a resistivity maximum,[15,16] is an open question. However, again T_{max} appears to reflect in a fundamental way the nature of interactions leading to the highly correlated electronic ground state in UBe_{13}.

Recently, Fisk *et al.*[31] have noted an intriguing correlation between the electronic specific heat per unit volume γ_V $(\equiv C_v/T)$ and the ground-state configuration of uranium-based heavy-electron systems. With increasing γ_V the sequence paramagnetic, magnetically ordered, superconductive appears. From the measurements of specific heat as a function of pressure on UBe_{13} by Olsen *et al.*,[9] we have constructed plots of $C(P)/T$ versus T from which the Sommerfeld coefficent could be estimated at $T=0$. For $P=9.3$ kbar, we find $\gamma(0) \simeq 630$ mJ/mole K^2. Using a value of 0.97×10^{-3} $kbar^{-1}$ for the compressibility of UBe_{13},[9] we have calculated γ_V to be 7.83 mJ/cm^3 K^2 at 9.3 kbar, which is almost one-half its value at ambient pressure and is approaching the values for $\gamma_V \simeq 5.3$ mJ/cm^3 K^2 of the heavy-electron magnets UCd_{11} and U_2Zn_{17}.[31] That pressure would promote a superconductor to become more like a magnet is certainly counterintuitive to our understanding of conventional superconductivity. Perhaps these pressure experiments are revealing that the intersite couplings responsible for producing a coherent spin-fluctuation spectrum at low temperatures are also the source of magnetic phase transitions in some heavy-electron materials and that it is only the ratio of intersite to intrasite energy scales that determines the ultimate ground-state configuration.

V. CONCLUSIONS

The electrical resistivity of UBe_{13} shows a strong response to pressure particularly at low temperatures where there is a cross over from intrasite to intersite dominated correlations in the electronic scattering. Below $T_{max} \sim 2.5$ K, the resistivity drops precipitously with increasing pressure indicating that the spin-fluctuation spectrum is becoming more fully coherent. For pressures greater than ~ 9 kbar, the resistivity increases as T^2 with the T^2 coefficient A decreasing monotonically with pressure in proportion to $1/T_{max}^2(P)$, as might be expected from a Fermi-liquid viewpoint. However, the field variation of A is nonmonotonic and passes through a maximum near 3 T. The origin of this anomalous behavior is not understood. At 14.8 kbar, the magnetoresistance is larger and negative and behaves as a universal function of H/T for $1 \lesssim T \lesssim 6$ K. From the field and pressure dependence of T_{max}, it appears that 1 T^2 is roughly equivalent to 100 bar in so far as their effects on T_{max} are comparable. The importance of T_{max} as a fundamental energy scale is reflected in the pressure response of UBe_{13}, particularly in that it appears to scale the $T=0$ electronic specific-heat coefficient γ and the electrical resistivity. Finally, analysis of the pressure dependence of γ normalized per unit volume indicates that UBe_{13} may be driven from a superconductive to magnetic-like state with pressure. Taken together with the results from resistivity measurements, this would suggest that it may be only the ratio of intersite to intrasite energy scales that determines the ground state of the heavy-electron system.

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